X-RAYS AND X-RAY APPARATUS

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X-RAYS AND X-RAY APPARATUS

AN ELEMENTARY COURSE

BY

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"The details of knowledge which are important will be picked up *ad hoc* in each avocation of life, but the habit of the active utilisation of well-understood principles is the final possession of wisdom."

(WHITEHEAD.)

PREFACE

For some years the writer has been giving courses of lectures to medical students on the physical principles underlying the use of X-rays and other radiations. While these have not been received with any greater enthusiasm than that which medical students are wont to display towards anything savouring of physics, they have served to strengthen the conviction that the application of any branch of science cannot be successfully taught, or understood, without a knowledge of fundamental principles. The science of medicine becomes more and more an application of the laws of physics, chemistry and biology, in consequence of which the problem of medical education is no easy one. Applications, moreover, continually change, sometimes, indeed, overnight, and yet the medical student must be familiar with advances in his profession. What is he or his teacher to do? To train only specialists is no solution, for even if we assume that all students have the necessary qualifications to be so trained (which is doubtful), it will be admitted that even a specialist must begin with a broad foundation. While the opinion of a physicist on such a question may be worth but little, it does seem to the writer that there should be an insistence on the kind of teaching which drives home the broad basic principles of the fundamental sciences. The student with a real grasp of principles fears no application.

In this book, therefore, an attempt has been made to present as clearly and as simply as possible the physical principles utilized in the field of radiology. While applications are discussed to a considerable extent, the emphasis is on the fundamental conceptions without a grasp of

which no intelligent practice or progress in this field is possible. It is hoped that the book will fill a need as a basis of instruction in the physical end of X-ray work, both in medical schools and in hospitals. As only a very elementary knowledge of physics has been assumed, it is hoped, too, that it may make an appeal to those medical practitioners in whose college days the curriculum did not include the subject of radiology.

The author has pleasure in taking this opportunity of expressing his gratitude to all those who gave assistance in the preparation of the book; in particular, to my colleague, Dean A. L. Clark, for helpful suggestions; to the authorities of Queen's University for placing at my disposal many facilities to expedite routine work; to Dr. Duane of Harvard University for permission to reproduce graphs; and to my wife for help with the index and general assistance throughout the preparation of the manuscript. For the gift or loan of electrotypes my sincere thanks are due Dr. W. D. Coolidge, the Wappler Electric Co., the Victor Electric Corporation, the International X-ray Corporation, the Waite and Bartlett Manufacturing Co., Geo. W. Brady & Co., and Mr. P. D. Ross of Stanford University. Most of the line diagrams were drawn by Mr. E. Harris of Queen's University and to him, too, I desire to express my appreciation.

J. K. R.

Queen's University,
Kingston, Canada,
July 21, 1924.

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CHAPTER I

THE INTERRUPTERLESS TRANSFORMER

1. To operate any type of x-ray bulb, a high voltage must be applied to the terminals of the bulb. By "high" is meant a voltage which is many times greater than any of those ordinarily available. To be more definite, a dry cell of the type familiar to everybody, has a voltage between its terminals of about 1.4 volt, while a small storage battery has a value of about two volts. Between the lead wires which deliver electric power to the average householder, the common voltage is 110, although by special arrangement a supply of 220 volts may be obtained. But before useful x-rays may be obtained from a bulb, voltages of the order of 20,000 or very much higher must be used. There are on the market machines making available 300,000 volts. How are these high values obtained?

At least three different types of machines have been used for this purpose: (1) the "electrostatic" electric machine, such as the Wimshurst; (2) the transformer; (3) the induction coil. The first type is of scarcely more than historical interest in these days of powerful x-ray outfits, and need not be considered in this book. It is highly desirable, however, that every user of an x-ray bulb be familiar with the

second and the third types and each of these will be discussed in detail. Both are based on two important fundamental principles: first, that of electro-magnetism; second, that of electro-magnetic induction. Before proceeding to an explanation of these, a few simple electrical terms will be defined.

2. **The volt** is a unit of electrical pressure, or speaking more scientifically, of difference of potential. Voltage or difference of potential is always necessary before any current can flow, just as difference of pressure is necessary before water will flow along a pipe. Voltage, however, is not current any more than water pressure is the volume of water flowing per second.

Voltages available may be one of two types, (1) D.C. (direct current), where the polarity never reverses, (2) A.C. (alternating current), where the direction is continually reversing. A dry cell has a voltage of 1.4 (D.C.), while the ordinary house is generally supplied with 110 (A.C.).

The **ampere** is the practical unit of current and has to do with the quantity of electricity flowing past any point in a circuit per second. To make the matter more concrete, when 110 volts are applied to a 20 watt tungsten lamp, a current of about one-fifth of an ampere is flowing through the lamp; when a 600 watt electric iron is joined to the 110-volt lighting circuit, a current of from 5 to 6 amperes is flowing through the iron. The voltage causes the flow but the current (again the quantity of electricity passing a point per second) depends both on the voltage and on the opposition to the flow between the points to which the voltage is applied—that is, it depends also on the resistance. To use a water analogy once more, water pressure causes a flow but the quantity of water flowing per second through a pipe depends both on the water pressure and on the size of the pipe.

A **rheostat** is a simple device for altering the amount of wire in an electric circuit, that is, of varying the resistance

and, therefore, of regulating the magnitude of the current (within limits).

In Figure 1, if the movable arm AB is in position I, the current flows through coils 1 and 2; if the arm is moved to position II, the current must flow through coils 1, 2, 3, 4, that is, against a greater amount of resistance. Hence the current in the second case is smaller.

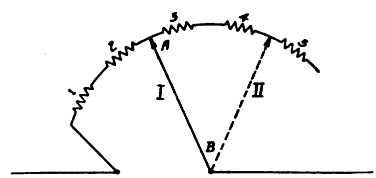

FIG. 1.—A simple rheostat, with five coils.

A **milliampere** is just one-thousandth of an ampere. As will be seen later, the current flowing through the primary of an x-ray transformer is measured in amperes, possibly as high as 30, while the current through the x-ray bulb itself is such a small fraction of an ampere that its magnitude is invariably given in milliamperes (ma).

THE PRINCIPLE OF ELECTRO-MAGNETISM

3. Most readers are familiar with the fact that when a small bar magnet is placed beneath a sheet of paper, and iron filings are sprinkled on it, the filings arrange themselves along regular lines somewhat as represented in Figure 2 (an actual photograph). This simple experiment indicates that in the whole region around the magnet there is what is called a magnetic field of force. To visualize this field we generally say that it is traversed by magnetic lines of force, the closeness of the lines of force at any particular place being a measure of the strength of the magnetic field at that place. These lines of force are closed curves leaving the North pole of a magnet, entering the South pole and we say there is a magnetic flux through the magnet. Indeed, whenever magnetic lines are passing through any region, we speak of a magnetic flux through that region.

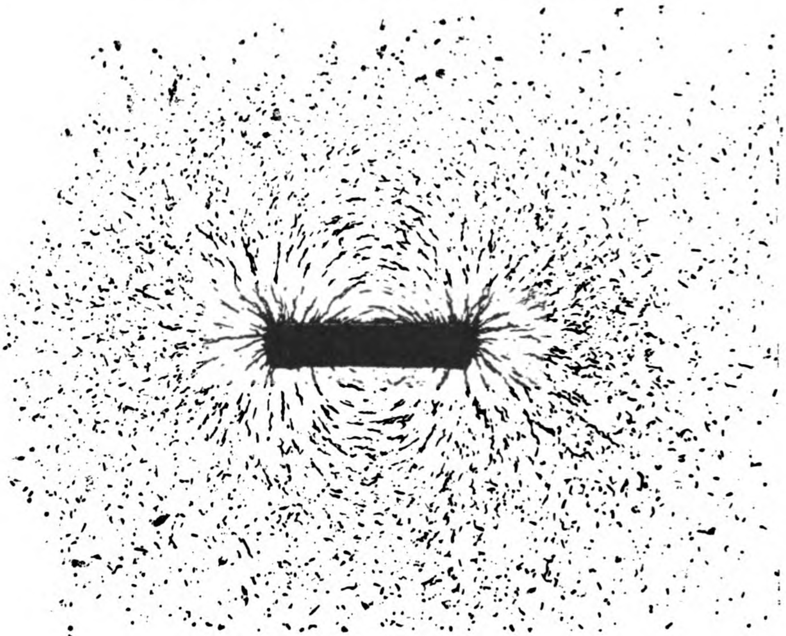

FIG. 2.—Iron filings about a bar magnet.

Suppose, now, that the wire AB (Fig. 3) is carrying a current of several amperes, and we sprinkle iron filings on a sheet of paper through which the wire passes. We find that, so long as the current is flowing, the filings are arranged in circular lines with the wire as center. *A magnetic field, therefore, surrounds a wire carrying a current.* This is the fundamental principle of electro-magnetism. *We can have magnetic fields subject to the control of an electric current.* If a wire carrying a current is wound

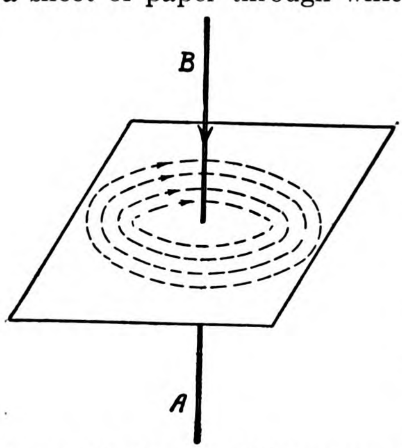

FIG. 3.—Circular lines of force encompass a wire carrying a current.

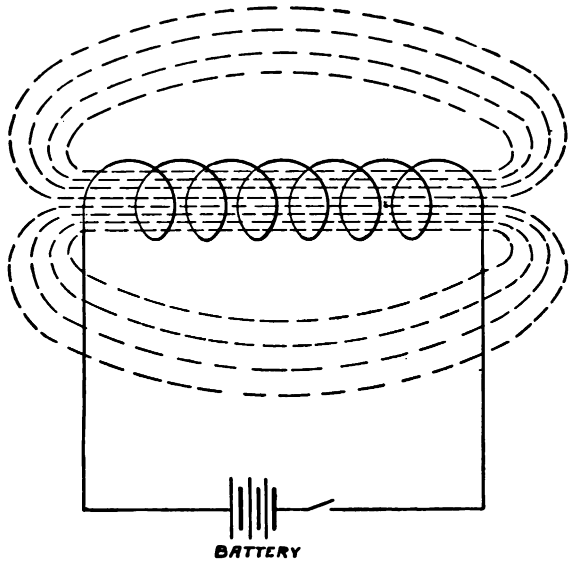

FIG. 4.—Lines of force are linked with a solenoidal coil carrying a current.

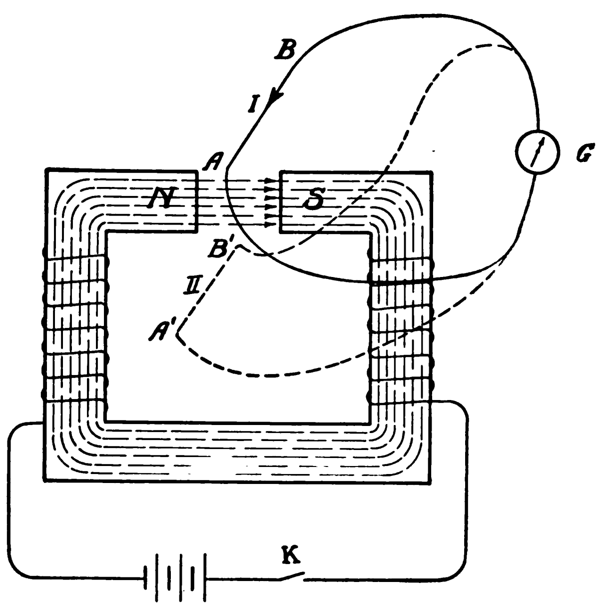

FIG. 5.—Simple experimental arrangement to demonstrate cause of an induced current.

into what is called a solenoid (Figure 4) it can easily be shown that one end of the solenoid acts as the North, the other end as the South pole of a bar magnet with magnetic lines of force somewhat as represented in the figure. Obviously these lines are linked with the electric circuit, and at once disappear when the electric circuit is broken. If the air inside the coil be replaced by soft iron, the soft iron becomes strongly magnetized under the influence of the magnetic field due to the current, and the number of lines of force may be increased many times. We have in fact an electro-magnet. Break the circuit, the lines of force disappear; make the circuit, the lines of force are introduced. Electro-magnets are frequently of the shape illustrated in Figures 5 and 6.

The Principle of Electro-Magnetic Induction

4. This may best be explained by reference to one or two simple experiments. Suppose we are provided with an electro-magnet of the type illustrated in Figure 5 (where the lines of force are again represented by dotted lines). Imagine, also, a simple electric circuit containing a wire AB which may be readily moved, a current-measuring instrument G, *but no cell or battery or other source of voltage.* Suppose next the switch K controlling the electro-magnet circuit is closed and in this experiment left so. If, now, the wire AB is moved from position I across the lines of force to position II (A′B′) a momentary current will be indicated by G, the measuring instrument. If the wire be moved back again, a momentary current in the opposite direction is recorded. In general, it will be found that as long as the wire is cutting the lines of force, there is a current whose direction depends on the direction of motion of the wire. Such a current is called an induced current, the voltage causing it, an induced E.M.F. (electro-motive force). *Whenever, therefore, a portion of any circuit is moving with reference to magnetic lines of force, there is*

an induced E.M.F. (voltage) in that portion of the circuit, and if that circuit is closed a current results. This is the very important principle of electro-magnetic induction.

The principle may be stated in another and possibly more useful way. This will be evident from another look at Figure 5. When the movable wire is in position AB, there are no lines of force linked with this circuit, but when it is in position A′B′, all the lines of the electro-magnet are linked or interlocked with it. We frequently say, therefore, that an induced voltage results in an electric circuit whenever there is any *change* in the number of lines of force linked or interlocked with it. To emphasize this, we shall perform another experiment. Imagine the movable wire in position A′B′. If, now, the electro-magnet circuit (which we shall call the *primary*) is *broken,* a momentary induced current results in the movable wire circuit, which we shall call the *secondary.* Again when the primary circuit is *made,* a momentary current in the opposite direction results in the secondary. In this experiment, the secondary circuit is not moved, but the magnetic lines of force either disappear or reappear. There is therefore relative motion of magnetic lines and a portion of a circuit, and so an induced current results. Putting it in the other way, at "break" of the primary, there is a decrease in the number of lines linked with the secondary; at "make" an increase—in both, a change, and an induced voltage results.

Magnitude of Induced Voltage

5. This involves a consideration of two other points. (1) If the wire AB (Figure 5) be moved from position I to position II at two different rates, for example, one ten times faster than the other, it will be found that the induced current is just ten times as great, although it will, of course, last for a correspondingly shorter time. In other words, the magnitude of an induced voltage depends on the *rate*

at which the change in the number of linkings takes place. The faster the change, or the more quickly lines are cut, the higher the induced voltage. (2) If the secondary circuit be altered as represented in Figure 6, so that the magnetic lines of force link the circuit twice, it will be found that on "break" of the primary circuit the induced voltage is twice that obtained previously. If the secondary

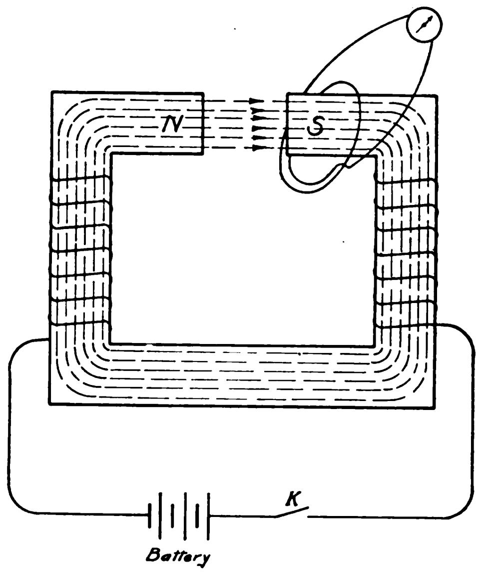

FIG. 6.—A coil linked twice with lines of force of an electromagnet.

circuit links the lines ten times, then the induced voltage would be ten times as great, and so on.

To sum up: The magnitude of an induced voltage in any circuit depends, (1) on the rate at which a change in the number of magnetic lines linking a circuit takes place, and (2) on the number of times the lines are linked with the circuit. It follows, therefore, that if a circuit is linked a large number of times with magnetic lines, and these disappear (or are introduced) very quickly, extremely high voltages may be induced.

Meaning of A.C.—Sinusoidal

6. Suppose a single loop of wire, ABCD, Figure 7, is rotated in the region between two powerful magnetic poles N and S. As the wire AB goes down it cuts across lines of force and in it we have an induced voltage in the direction of the arrow. At the same time the portion of the loop CD goes up, thus cutting the same lines in the opposite direction, and an induced voltage in the opposite direction

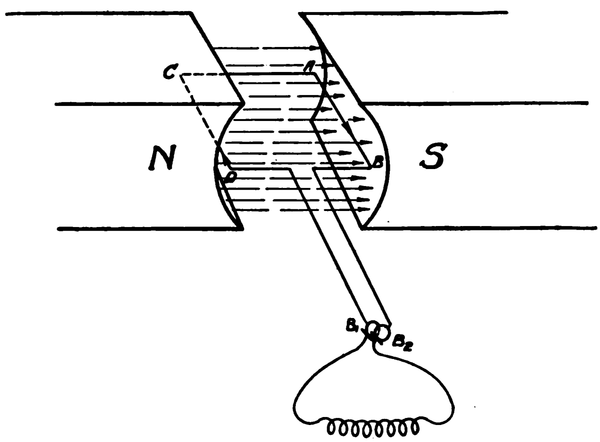

Fig. 7.—A simple arrangement to generate a sinusoidal current.

(Section 4) results. If, now, the ends of the loop are connected to two slip rings upon which rest brushes B_1 and B_2 connected by some external conducting circuit, an induced current may flow. Evidently all the time AB is going down and CD up (that is, for half a revolution) a circuit will flow through this circuit in the direction indicated by the arrows. After AB has reached its lowest position, however, it begins to move up, and then the direction of the induced voltage will change. At the same time, the wire CD will have reversed its direction (up to down) and in it too the induced voltage reverses. It follows, therefore, that during the second half revolution the current throughout the cir-

cuit will flow in the opposite direction to that during the first, and that as rotation continues, the current reverses in direction every half revolution.

Not only, however, is there a reversal of current (or, if you like, of polarity between the brushes B_1 and B_2) but the *strength* of the current is continually changing. This will be evident if it is realized that when the wire AB is passing through its highest position and the wire CD through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As AB goes down (and CD up) the lines are cut more and more quickly until after one-quarter of a revolution both AB and CD are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the biggest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until AB reaches the bottom (CD the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero, from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Figure 8.

A current of this type is an *alternating* one (A.C.) as well as *sinusoidal*. Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual "smooth" changes in intensity. In passing it may be noted that by using a mechanical means, such as a revolving drum, to put in and take out resistance gradually from a circuit, sinusoidal effects without changing polarity may be obtained.

It is well to note that while a sinusoidal current is always A.C., it is possible to have alternating currents which are not sinusoidal.

Two or three important terms should be noted.

A **cycle** refers to the complete change from zero to a maximum in one direction, down through zero to a maximum in the other direction and back again to zero. In Figure 8, OA represents a cycle.

The **frequency** of A.C. is the number of cycles per second. Most householders on the American continent are supplied with A.C. at 110 volts, with a frequency of 60 or 30 cycles per second.

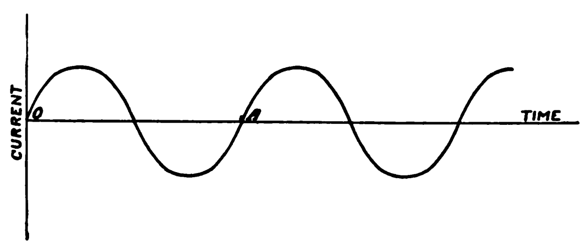

FIG. 8.—Graphical representation of a sinusoidal current.

Neither this voltage nor this frequency could be generated with a simple machine of the type illustrated. In the practical A.C. generators or dynamos found in power houses, the desired frequency and voltage are obtained by using several sets of magnet poles, alternately north and south, and many loops of wire. The fundamental principles utilized, however, are the same as those we have been discussing and the current supplied by such generators generally approximates fairly closely to the sinusoidal.

THE HIGH TENSION TRANSFORMER

7. We are now in a position to explain the principle of the high tension transformer.

In Figure 9, ABCD represents a series of sheets of soft iron put together to form a "core" of iron of the shape illustrated. A coil of wire P, the primary, which is connected with a source of 110 volts (A.C.) is wrapped about one

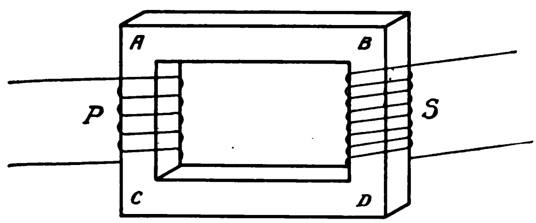

FIG. 9.—A simple transformer.

arm of the iron core. When this primary circuit is closed, the alternating current will magnetize the iron core, first with lines running in one direction, then in the opposite.

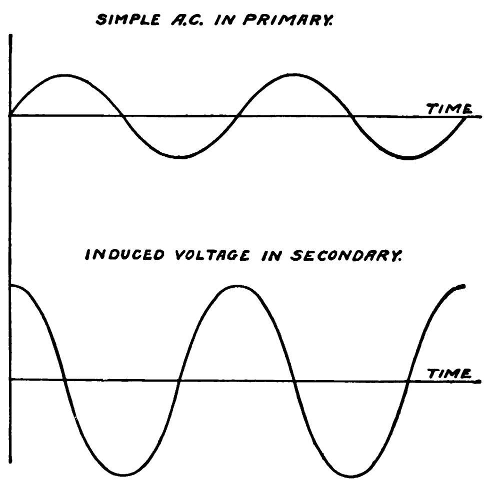

FIG. 10.—Graphical representation of alternating current in primary of a transformer, with corresponding induced voltage in secondary.

Suppose, now, a second coil S, the secondary, is wrapped about another portion of the iron core. Evidently the magnetic lines, when present, are linked with each turn

of this coil. Moreover, the number of lines linked with the coil is continually changing. As the number of lines is rising to a maximum (increasing) in one direction, we shall have an induced voltage in coil ~~P~~ S in one direction; as the number decreases there will be an induced voltage in the opposite direction. Without going into further detail, corresponding to current changes in the primary, there will be induced voltages in the secondary which vary in the manner represented in Figure 10.

There is, therefore, an induced voltage in the secondary which is alternating (A.C.) and of the same frequency as that of the primary. Concerning the magnitude of this induced voltage, it should be evident (Section 5) that by using a large number of turns in the secondary, extremely high values may be obtained. As a matter of fact, the voltage is "stepped-up" roughly in the ratio of the number of turns of the secondary to the number of turns of the primary. High tension transformers are now on the market which it is the claim of the makers will deliver a voltage as high as 300,000.

Necessity of Rectification

8. For the satisfactory use of any x-ray bulb the current flowing through it must always be *uni-directional.* It may be intermittent but unless its direction is always the same, and correct, the results on the tube may be disastrous. As a rule, therefore (one or two exceptions will be noted later), the high tension transformer because it delivers alternating current, is not sufficient for a complete x-ray high voltage outfit. Some device must be added so that the current through the tube is always in the same direction. Either one-half of the cycle must be suppressed altogether, or, by means of what is called a rectifier, the alternating voltage between the high tension terminals of the transformer must be applied to the tube with unchanging polarity. In the so-called interrupterless transformer such a device is added.

The principle is simple and should be clear from a consideration of Figures 11 and 12.

In these figures, A and B represent heavy lead wires coming directly from the high voltage side of a transformer. Each circle represents a disc, which may be rapidly rotated and is made of some good insulating material. Attached to the disc are four projecting pieces of metal (1, 2, 3, 4), 1 and 2 being connected by a piece of wire, similarly 3 and 4. (An actual photograph of such a disc is shown in Figure

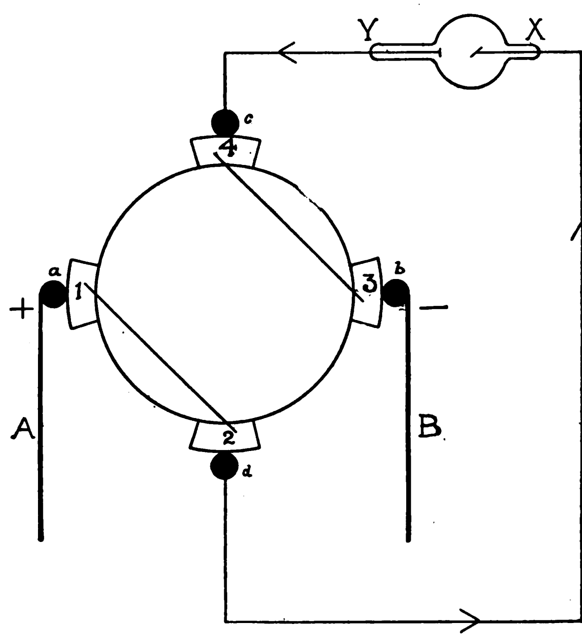

FIG. 11.—Rectifying Disc.

12A.) As the disc revolves, these pieces touch fixed metal brushes (*a, b, c, d*), *a* and *b* being attached to the lead wires A and B, while by means of *c* and *d* connection may be made with a circuit containing an x-ray bulb. Suppose, now, that as the disc rotates, it reaches the position indicated in Figure 11, at the moment the voltage between A and B is a maximum (the "peak" of the sinusoidal curve),

A being +, B —. At that instant, then a current will flow from A to *a* to 1 to 2 to *d*, through the bulb in direction X to Y, back to *c* to 4 to 3 to *b* to the other lead wire B. Suppose further that during the time of one-half a cycle, the disc revolves to position shown in Figure 12. In that case, since the voltage between A and B is now once more

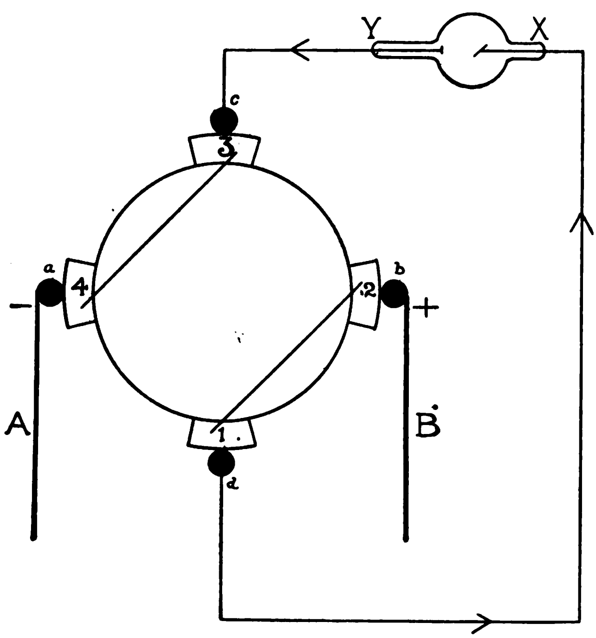

FIG. 12.—Position of Rectifying Disc half a cycle after that of Fig. 11.

a maximum, but with A — and B +, a simple inspection of the diagram in Figure 12 will show that the current flows from B to *b* to 2 to 1, through the bulb in the same direction as before, to 3 to 4 to *a* to A. In other words, if the disc can be rotated at this very exact speed, then the current through the bulb will always be uni-directional. In the transformer secondary coil, of course, it is alternating just as before. This exact co-relation between the speed of the rectifying disc and the frequency of the alternating current

is obtained by means of what is called *a synchronous motor.* Before an explanation of the principle of the synchronous motor is given, it is well to note that, although the current through the tube with the above arrangement is unidirectional, it is also *intermittent.* A glance at Figure 13

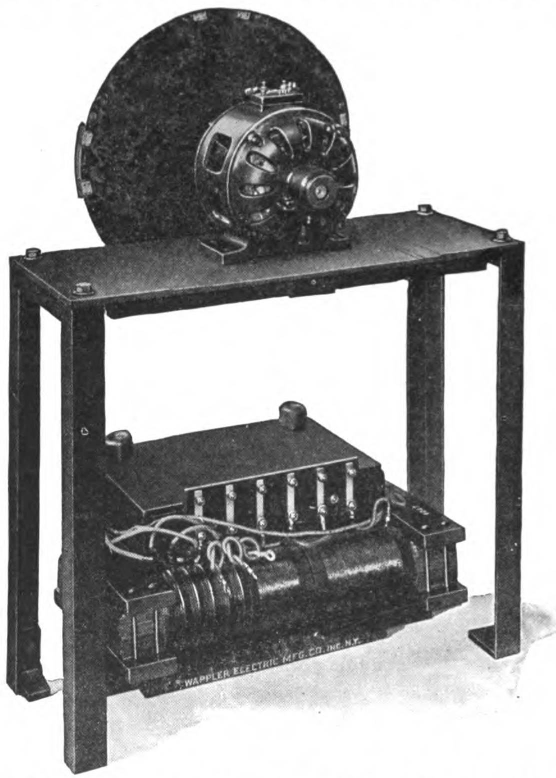

FIG. 12A.—Photograph of Rectifying Disc (Wappler Electric Co.)

should make it clear that when the disc is in the position indicated in that diagram, there is no current through the tube because neither *a* nor *b* touches a metal projection. Evidently the length of time the current is flowing will depend on the size of the projecting pieces, that is, on the time they are in contact with the lead wires A and B (see, however, Section 17). This time interval, therefore, may

be and probably is different in different machines. If it is very short, only the "peaks" of the voltage values will be utilized as represented graphically by the short heavy line in Figure 14 (a). If the time interval is a little longer, a greater portion of the whole range of voltage values will be utilized, the short heavy lines extending to the dotted parts. It is well to note further that, in order to utilize the peak voltage, the disc must be in proper alignment, that is, when

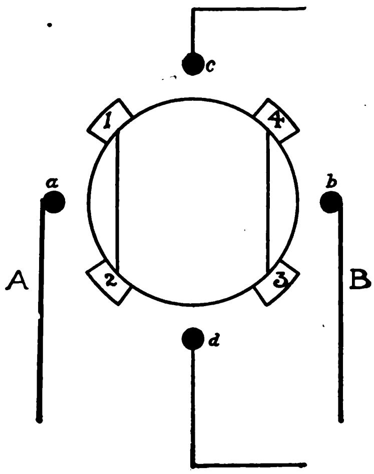

FIG. 13.—Position of Rectifying Disc when no current is passing.

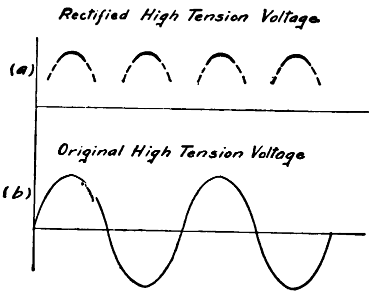

FIG. 14.—Graphical representation of effect of rectifying disc on original high tension voltage.

it is in the position represented by Figure 11, the voltage across A and B must be at its maximum value. Sometimes the disc slips on its rotating axis and gets out of alignment. To readjust it the services of an electrical engineer may be necessary.

In actual practice it is found that the high tension voltage curve departs from the sinusoidal form, and indeed varies somewhat with the conditions under which the tube is being used. The effect of this on x-ray measurements will be seen later. In the meantime, while Figure14 is more or less ideal,

that in no way affects the general truth of what has been said.

The Synchronous Motor

9. Neither radiographers nor therapists nor even physicists can be expected to be familiar with the detailed construction of synchronous or indeed other types of motors. That is the work of the electrical engineer. For anyone to operate an x-ray outfit intelligently, however, it is necessary to understand the basic principles utilized in the apparatus one is handling. A simple explanation, therefore,

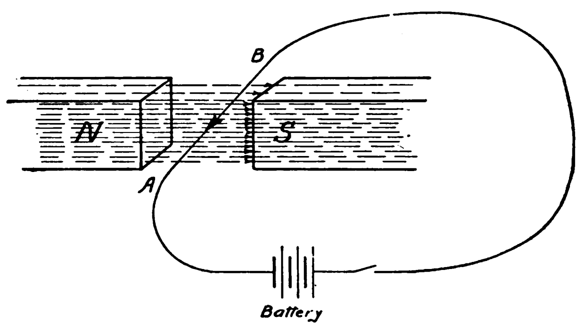

Fig. 15.—Simple arrangement to demonstrate the motor principle.

of one type of synchronous motor will be given. As is the case with all motors, there is one fundamental underlying principle which we shall call the motor principle.

In Figure 15, AB represents a wire which is part of a circuit *including a battery or some other source of voltage.* If this wire lies in a magnetic field as illustrated, and it is free to move, it will be found that on completing the circuit of which it is a part, the wire is pushed either up or down. With the current in the direction of the arrow, motion is up; with current in the opposite direction, motion is down. This simple experiment which may readily be performed, illustrates the motor principle. *Whenever a wire carrying a current lies in a magnetic field, because of the interaction between this magnetic field and that due to the current*

(Section 3), *the wire is acted on by a force.* If the wire lies at right angles to the magnetic field, as in Figure 15, it is pushed at right angles both to the lines of force and to itself; one way, for current in one sense, the opposite way for current in opposite direction. Anyone familiar with the electrocardiograph apparatus will recognize the same principle utilized in the Einthoven galvanometer.

Now let us apply this principle to a coil ABCD (Figure 16) free to rotate in the region between two magnet poles,

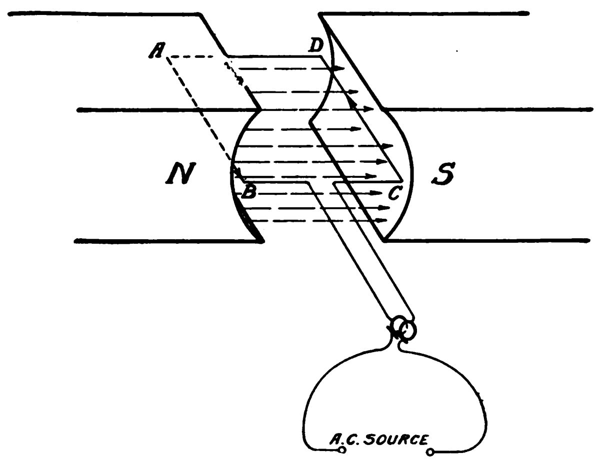

FIG. 16.—An ideal diagram of an A.C. motor.

and supplied with *alternating* current. Suppose the coil is at rest in the position shown, when the current is in the direction of the arrows. Then CD will experience a push down, AB up, and the coil will start to rotate. If, however, the current is alternating and the coil has any inertia to speak of, before it has had a chance to rotate an appreciable amount, the current will reverse, and the forces on both AB and CD will reverse also. As a consequence there will be no actual rotation. Suppose, however, that by some external means the coil is previously rotated at such a speed that it just reaches the vertical position at the moment

the alternating current is passing through the zero value. This means that when the current begins to flow in the reverse sense a push on CD in the upward (reverse) sense will simply help to keep the coil rotating in the same way. Again, after another half revolution, CD will be at its highest position and ready to go down when the reversal takes place. *There is, therefore, a very special speed such that a coil will keep rotating in synchronism with the changes in an alternating current.* Once it is brought up to this speed by some external means, it keeps running at exactly the same rate, because, once more, the reversals of current take place at just the right instant to cause rotation always in the same sense. In an interrupterless transformer outfit, therefore, the rectifying disc is rotated at the required exact speed by means of a synchronous motor. It is neither necessary nor advisable to discuss the practical details of its construction. We have sought only to explain the basic principle of a type in common use, and we have done so partly to show why in so many x-ray machines some device is necessary for bringing the synchronous motor up to speed. In some machines a starting motor of another type is added solely for this purpose. In others a starting switch closes a branch circuit in the synchronous motor and has the effect of making it temporarily another type of motor until it comes up to speed. In others there is a single synchronous motor built on a different principle, which comes up to speed without any external aid.

A Simplified Interrupterless Transformer

10. We are now in a position to consider the operation of a simplified but complete x-ray transformer outfit. In Figure 17, X and Y represent main leads, 110 or 220 A.C. The mains branch into two circuits, one supplying current to the synchronous motor, and controlled by Switch I; the other supplying current to the primary of the high tension

transformer, controlled by Switch II. In addition, there is the high tension circuit, including the secondary of the transformer, the x-ray tube and a milliamperemeter, with the rectifying disc placed so as to send a uni-directional current through the tube. The diagram should make clear without further explanation the connections of the tube circuit. It may be stated, however, that the parts of the rectifying arrangement are labelled as in Figures 11 and 12,

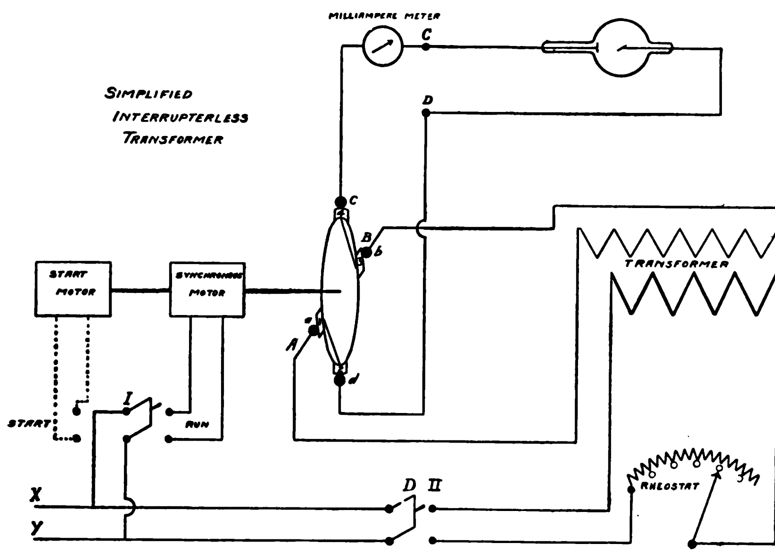

FIG. 17.—Simplified connections of an interrupterless transformer.

and that C and D correspond to the high tension terminals usually found on the top of the x-ray cabinet which "houses" the transformer, the motor or motors, and the disc.

To operate, then, with such an arrangement, the tube is first placed in position and connected by means of extensible wires to the high tension terminals C and D. This circuit is then closed and is as illustrated in the figure. Next the synchronous motor is brought up to speed. In the arrangement we are considering this is done by throwing Switch I to the side marked "start," thus utilizing the start-

ing motor, until the requisite speed is attained. Switch I is then thrown to side marked "run" and left there. The rectifying disc is now running at the necessary exact speed and may be left so for some length of time. As noted above, in other types this procedure would be slightly different. In the case of some machines it is simply necessary to close a switch corresponding to Switch I above.

Finally to use the x-ray tube, Switch II, the so-called x-ray switch, is closed, thus supplying the primary of the transformer with current, and so causing an induced high voltage in the secondary, which in its turn causes a current to flow through the bulb and milliamperemeter in the closed secondary circuit. The strength of this current may be altered by putting in or taking out resistance by means of the rheostat.

Direction of Current Through the Tube

11. Not only must the current through an x-ray tube be uni-directional but it must be in the right direction. Now, if one went through the series of operations which have just been outlined, it might be found on closing Switch II that the current was going through the tube in the wrong way. Just how one would know that will be explained later. In fact, if one began one hundred times at the beginning, with all the switches open, it would be found that on closing the x-ray Switch II, on the average, fifty times the x-ray current would be in right direction, fifty times wrong. In other words, with the above arrangement and procedure, it is just an even chance whether current is right or wrong. A glance at Figure 11 will explain the reason for this. In this figure it has been assumed that when the disc is in the position indicated, A is positive and B negative. Now, when it is brought up to speed, there is just as good a chance of A being negative and B positive, as vice versa. If that were the case in Figure 11, then the current through

the tube would always flow from Y to X, not X to Y. With the above simplified arrangement, therefore, when the x-ray switch is closed, one would never know whether the current through the tube would be in the right or the wrong direction. If it were wrong, it would then be necessary to open the motor switch and close it again until the right direction was obtained. Now such a procedure is bad for the tube. How, then, can it be avoided?

The Polarity Indicator

12. There are at least two ways, one inconvenient and seldom used; the other in constant use in connection with almost every interrupterless transformer on the market.

The first consists in having a "point-plane" spark gap connected to the high tension terminals, and by closing Switch II before the bulb is placed in position, allowing a spark to "jump" the gap. If the spark "jumps" as indicated in Figure 18, that is, from point to central portion of the disc, the point is positive; if the spark is as illustrated in Figure 19, from point to periphery of the disc, the point is negative. By this means the polarity of the high tension terminals on the cabinet is determined before the tube is placed in position. It should be noted, however, that every time the synchronous motor is stopped, the same procedure would have to be repeated before subsequent use of the tube.

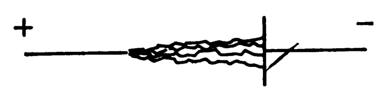

Fig. 18.—Appearance of spark, point positive.

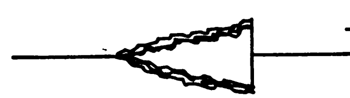

Fig. 19.—Appearance of spark, point negative.

A much more convenient method is found in the use of the *polarity indicator,* a small instrument found on the switchboard of nearly every interrupterless transformer. The instrument is a direct current ammeter, with a pointer

which moves to the left of a zero for current in one direction, to the right for current in the opposite direction. It is placed in a branch circuit taken off the motor circuit, and through it flows a current which has been rectified. When the synchronous motor has come up to speed, therefore, the pointer is deflected to one side or to the other, depending on which way the current has been rectified. Suppose, now, with any given outfit, it is noted once for all, when the polarity indicator needle moves to the right, which of the high tension terminals is positive. To do so the x-ray switch would have to be closed. Then subsequently whenever the polarity indicator points in the same direction,

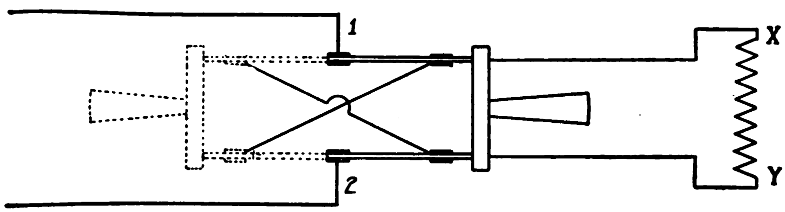

FIG. 20.—A Reversing Switch.

the same terminal would be positive, because each circuit is supplied from the same A.C. source.

If the polarity indicator points in the opposite direction, what then? This simply means that the high tension terminals are of opposite polarity to that previously determined. Now practically it is convenient always to work with a tube joined to the terminals in the same way. With the arrangement we are considering, therefore, it would be necessary to keep on opening and closing the motor switch until the polarity indicator finally pointed in the desired way. This, however, is not convenient. In actual practice, therefore, another switch, the pole changer or polarity switch, this time simply a reversing switch, is sometimes placed in the primary transformer circuit. By means of this the direction of the current through the primary may be reversed at any instant. Referring to Figure 20, if at a

certain moment, terminal 1 is +, 2 — and the switch is thrown as indicated, current will flow through XY in direction X to Y; if, however, switch had been in dotted position, current would have been through XY in direction Y to X. Accordingly, when the polarity indicator points the opposite way, without opening the motor switch, it is possible to change the polarity of the high tension terminals to that desired by simply reversing the polarity switch. In some machines the original wiring is such that, when the

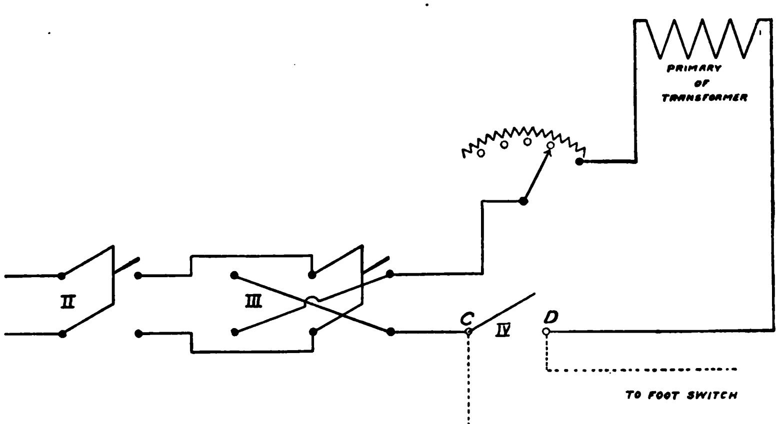

Fig. 21.—Connections of primary circuit, including x-ray switch, reversing switch and device for foot switch.

polarity indicator moves to the right, the correct position of the polarity switch is also to the right, and vice versa.

In Figure 21 the primary transformer circuit is re-drawn to show the polarity switch (III) as well as the way in which a foot switch is used.

The Foot Switch

13. Sometimes an operator may need the use of both hands and it is then convenient to be able to operate the tube by one's foot. When this is the case, the transformer primary line is broken at any convenient place (C and D,

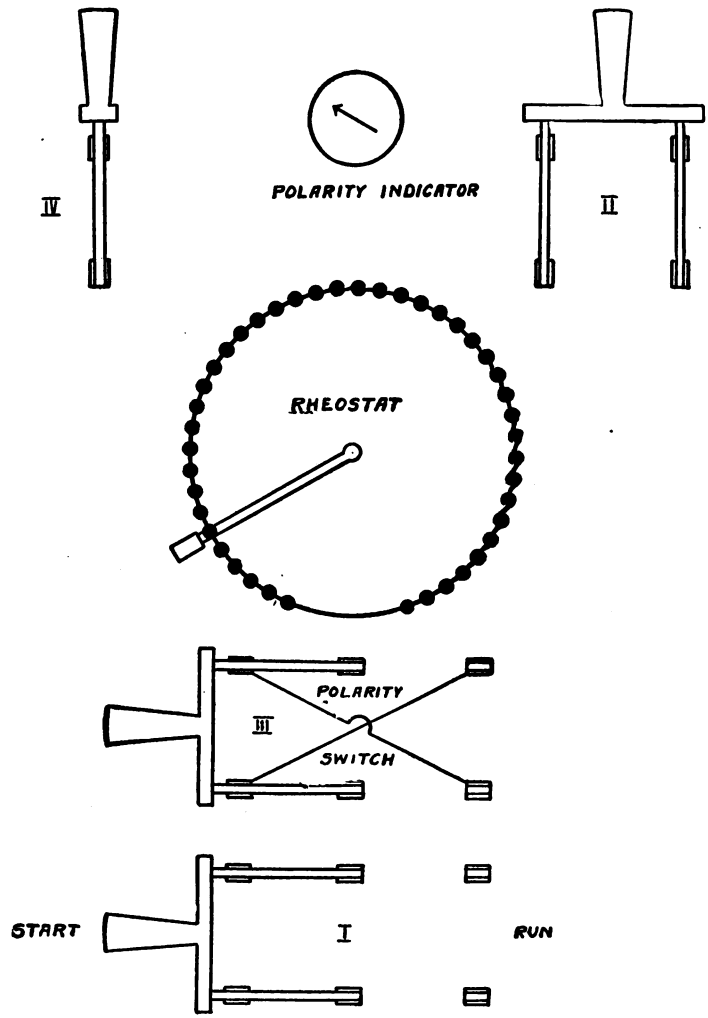

Fig. 22.—Possible appearance of switch board or control stand of an interrupterless transformer.

Figure 21) and two wires are led from each side of the break to a switch (not shown), the two parts of which may be pressed together by means of the foot. If one does not wish to use the foot switch, it is necessary simply to close a small single knife switch (IV, Figure 21), connecting C and D. If it is desired to use the foot switch, then first of all Switch IV must be left open, x-ray Switch II must be left closed, while finally the tube is operated by closing the transformer circuit with the foot switch.

14. In actual practice, for convenience, the various switches and controls are usually all placed on a common switchboard. Figure 22 is a diagram of the appearance such a switchboard might have to correspond to the type of outfit we have been considering. Figures 29 and 75 are actual photographs of switchboards or control stands.

CHAPTER II

THE INTERRUPTERLESS TRANSFORMER
(Continued)

Measurement of High Voltage

15. In Section 10 it was stated that the strength of the current flowing through the primary of the transformer might be altered by changing the amount of resistance in the circuit, that is, by moving the rheostat control. By this means the magnitude of the high voltage driving the current through the secondary (the tube) circuit may be altered. This raises certain questions. In any given outfit, what *is* the value of the high tension voltage? What is the range of voltages which may be obtained? What is the difference between different machines in this respect? Is the rheostat the only means of regulating the actual voltage across the tube? The answer to these and to other questions of the same nature will be given in the paragraphs which follow.

16. First of all, then, how is high voltage measured? This may be done in at least five different ways: by means of (1) the spark-gap, (2) a voltmeter across the primary terminals of the transformer, (3) the electrostatic voltmeter, (4) the so-called crest meter, (5) the Seeman spectrograph. Before looking briefly at each method, it is well to note that in x-ray work what is invariably wanted is the effective high voltage across the terminals of the tube when it is being used. This is not the same as the maximum voltage (E.M.F.) got up by the transformer.

To utilize the first method, a spark-gap consisting of two insulated conductors A and B (Figure 23) whose distance

apart may be varied, is placed in parallel with the tube. With the tube running, the distance between the gap terminals is gradually shortened until a spark takes place. *The length of this spark is a measure of the voltage across the tube or of what is technically called the "back-up" of the tube.* If the length of the gap is initially too great and it is slowly shortened, it should be evident that the "back-up" is a measure of the crest or peak voltage across the tube. (If readings are taken of spark length when tube is not in the circuit, a value of the maximum voltage got up by the transformer is obtained.)

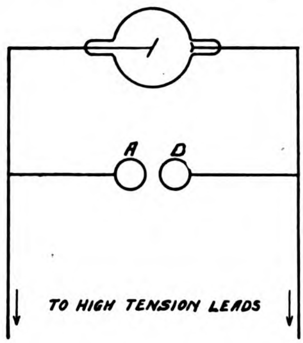

FIG. 23.—Connections for sphere gap.

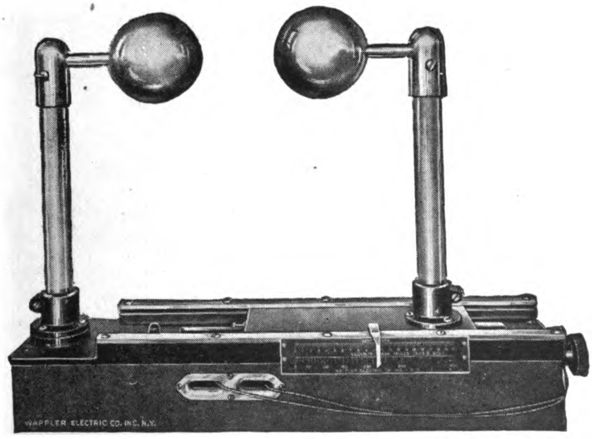

FIG. 23A.—Photograph of sphere gap (Wappler Electric Co.).

It is highly important to note that the sparking distance will depend on the nature of the terminals used. In practice, gaps between points, and gaps between spheres are utilized. Not only are voltage values for equal distances

very different in the two cases but even for sphere-gaps, the values vary with the size of the spheres. A glance at Table I (taken from Kaye and Laby's "Physical Constants,"

TABLE I

(Sparking voltages at 25° C. and 760 mm. pressure.)

Kilo Volts (Peak)	*Needle Points No. 00 New Sewing Needles*		*Spheres*		
			Diameter 5 cms.	*Diameter 10 cms.*	*Diameter 25 cms.*
	cms. gap.	inches gap.	cms. gap.	cms. gap.	cms. gap.
10	...	...	0.29	0.30	0.32
15	1.30	0.51	0.44	0.46	0.48
20	1.75	0.69	0.60	0.62	0.64
25	2.20	0.87	0.77	0.78	0.81
30	2.69	1.06	0.94	0.95	0.98
35	3.20	1.26	1.12	1.12	1.15
40	3.81	1.50	1.30	1.29	1.32
45	4.49	1.77	1.50	1.47	1.49
50	5.20	2.05	1.71	1.65	1.66
60	6.81	2.68	2.17	2.02	2.01
70	8.81	3.47	2.68	2.42	2.37
80	...	...	3.26	2.84	2.74
90	...	...	3.94	3.28	3.11
100	...	...	4.77	3.75	3.49
110	...	...	5.79	4.25	3.88
120	...	...	...	4.78	4.28
130	...	...	...	5.35	4.69
140	...	...	...	5.97	5.10
150	...	...	...	6.64	5.52
160	...	...	...	7.37	5.95
170	...	...	...	8.16	6.39
180	...	...	...	9.03	6.84
190	...	...	...	10.0	7.30
200	...	...	...	11.1	7.76
210	...	...	...	...	8.24
220	...	...	...	...	8.73
230	...	...	...	...	9.24
240	...	...	...	...	9.76
250	...	...	...	...	10.3

Edition IV) will show the way in which the spark length varies for different gaps. It will be noted, too, that for smaller voltages, the change in the distance, for a given change in voltage, is greater in the case of needle points, and for that reason, this kind of gap has an advantage for lower voltages. Its use is not to be recommended, however,

because the sparking voltage for a given distance varies with variable conditions, such as humidity, sharpness of points, etc. With the very high voltages used in deep therapy, a needle gap is useless. In this case the sphere gap as standardized by the American Institute of Electrical Engineers should be used.[1] Provided spheres are used whose diameters exceed that of the spark length, no such inconsistencies exist.

One of two further points, however, should be noted. The voltage corresponding to a given distance varies, not only with the size of the spheres, but also with the atmospheric pressure and air temperature. Table II for example shows the correction which must be applied to the

Table II

Temp.	*Press. 720 mm.*	*Press. 740 mm.*	*Press. 760 mm.*	*Press. 780 mm.*
0°	1.04	1.06	1.09	1.12
10	1.00	1.02	1.05	1.08
20	0.96	0.99	1.02	1.04
30	0.93	0.96	0.98	1.01

values given in Table I. To illustrate, with spheres of diameter 10 cm., at a pressure = 740 mm., and temperature = 20° C., the voltage corresponding to a distance of 2.02 cm. is not 60,000 but 60,000 × 0.99. Unlike the needle point, however, the sparking voltage for a given distance is independent of the humidity and the frequency (within the limits of values used in commercial A.C.). But because of changing spark length with size of spheres, temperature and pressure, it should be evident that the practice in x-ray of expressing the voltage across the tube by a spark *length,* even when a standard sphere-gap is used, should be discontinued. An accurate comparison of the work of one observer with another is possible only when voltages are expressed in kilovolts.

An objection to the use of a sphere-gap must next be

noted. With the gap set at a certain distance, a spark will jump whenever the potential difference between the spheres has the corresponding voltage value. This means that should this voltage be attained as a result of only a momentary surge in the circuit, sparking will still occur. Now, it will be seen when we come to the subject of dosage, that this may lead to erroneous conclusions, for the sudden rise in voltage may last for such a small fraction of the whole half-cycle, that the effect of the x-rays due to it, is almost negligible. To overcome this difficulty, so-called crest meters (Section 20) which do not respond to these short sudden rises are sometimes used. In spite of this objection, however, the use of a standard sphere-gap has much to be said in its favor.

17. The question of sparking voltages has an important bearing on the use of a rectifier such as was described in Section 8. It was there pointed out that the portion of the rectified half-wave utilized depended on the length of time the revolving metal pieces 1, 2, 3 and 4 were in contact with the fixed brushes. It should now be evident that *contact will be made as soon as the voltage is high enough to cause a spark to jump across the gap between the brush and the rotating part.* Since in the type of rectifier described (and most others) the metal pieces have sharp corners, it follows that we are here concerned with sparking between points. This means that there is much uncertainty about the exact portion of the half wave which is utilized. Indeed, there will be in general a variation with conditions, both electrical and atmospheric. Now, for ordinary radiographic purposes this may have no serious consequence; in deep therapy, however, as will be seen later, it is important to use always the same portion of the half-wave (and that the smallest possible). To meet this need, a so-called *constant rectifier* has been placed on the market. The principle utilized is exactly the same as that already described, but brushes in the form of spheres, and thick revolving parts with smooth

curved surfaces, are used so that sparking occurs essentially between spheres. By this means all the uncertainties of sparking between points are eliminated. A description of such a rectifier will be found in a pamphlet, *A Precision X-Ray Apparatus,* by Montford Morrison, of the Acme X-Ray Company, Chicago. The nature of the revolving parts is clearly shown in Figure 23B, in which one also sees the synchronous motor, as well as the casing enclosing the high tension transformer.

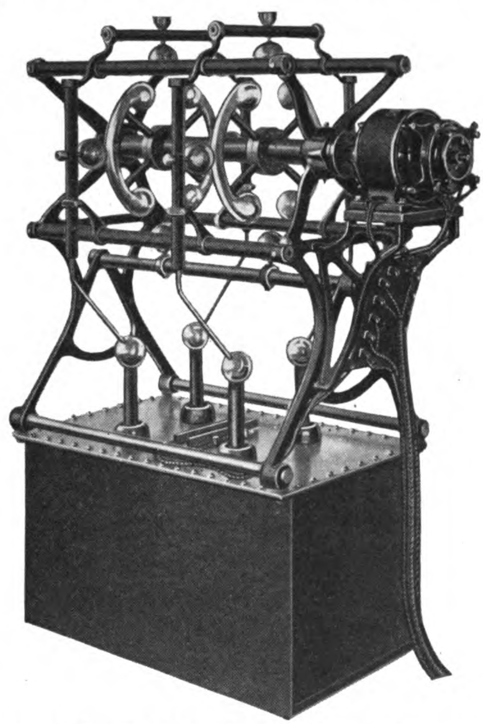

FIG. 23B.—Photograph showing constant rectifier, synchronous motor and enclosed transformer (Acme International X-Ray Corporation).

17A. Before leaving this subject of sparking potentials, we may call attention to the difference between a "corona" or "brush" discharge, and a spark. In the latter case the electric field between two conductors has become so intense that the air resistance breaks down along practically a continuous path between them. A discharge passes, accompanied by a crackling sound and marked luminosity. If, however, one or both of the conductors are pointed, the electric field in the neighborhood of the points may become so intense that a feebler discharge takes place. This dis-

charge is accompanied by a faint violet glow called the "corona." Obviously it is desirable to eliminate this type of discharge as much as possible, hence the use of so-called coronaless apparatus. In the case of spheres of large diameter the electric field is fairly uniform and corona does not exist. (See also Section 42.)

18. A second means of measuring the "back-up" of a tube is found in the use of an ordinary A.C. voltmeter across the primary terminals of the high tension transformer. As the primary voltage changes, so, too, will the high tension voltage. Accordingly, for any given machine, the ordinary voltmeter may be calibrated once for all, and an exact relation obtained between its readings and the high voltage across the tube. To do so, it is necessary to utilize a standard sphere-gap and to take simultaneous readings of back-up and of primary voltmeter. Unfortunately, to quote from a recent article [2] by Dr. W. D. Coolidge and W. K. Kearsley, "the primary voltage required to produce a given high tension voltage will depend on the milliamperage (that is, on the current through the tube). It is then necessary to calibrate against the sphere-gap for the exact milliamperage which is to be employed." Another objection to this method is found in the fact that a very slight change in the primary voltage may mean a considerable change in the high tension voltage, although by proper design of the transformer this may be minimized to some extent. In spite of these objections a primary voltmeter, accompanied by a calibration table for different milliamperages, should be useful. In Figure 75 such a voltmeter can be seen on the control stand top.

Electrostatic Voltmeter

19. The fundamental principle involved in the use of electrostatic voltmeters may be described by giving the details of one used by Dr. William Duane of Harvard University. This instrument consists essentially of a fixed part,

two large metal spheres X and Y (Figure 24) mounted on a highly insulated support, and a movable part, consisting of two metal balls A and B suspended so as to be free to rotate about a vertical axis. In using the instrument one side of the tube is joined to earth (grounded), while the other side (the target) is joined to the insulated metal balls of the instrument. As the movable balls are joined to earth there exists between the fixed and the movable parts of the voltmeter the same potential difference as between the two sides of the tube. The part AB rotates an amount which depends on this difference of potential, hence the magnitude of the latter is obtained by reading the deflection. It is, of course, necessary to calibrate the instrument by comparison with a standard sphere-gap, or by using known high voltages such as were available for Dr. Duane.

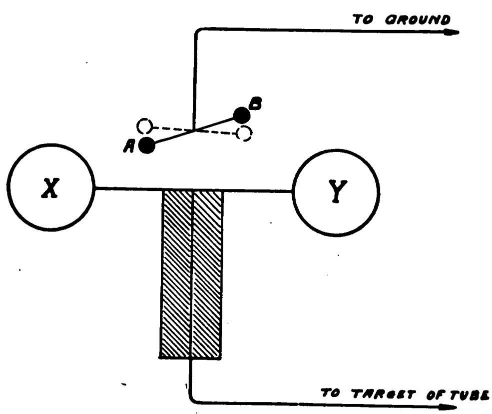

FIG. 24.—Arrangement of an electrostatic voltmeter (after Duane).

In passing it may be noted that the Bauer qualimeter (Section 80), an instrument used to measure the penetrating power of x-rays (to be discussed later) is essentially an electrostatic voltmeter.

THE CREST METER

20. To avoid the error in connection with the use of a standard sphere-gap when momentary surges in the voltage occur, the use of the so-called *crest meter* has been recommended. In this instrument use is made of the means originally employed by Fortescue and Chubb [3] for calibrat-

ing fundamentally a sphere gap. An air condenser (see Section 33) is charged by the high voltage (to be measured) across the tube and the charge stored in the condenser is discharged through a galvanometer. Now, since for the same condenser the current (when the condenser is rapidly charged and discharged) is proportional to the voltage to which it is charged, it follows that the deflection of the galvanometer is proportional to the voltage. Accordingly, with such an arrangement the scale on the galvanometer may be marked so as to read the number of kilovolts across the tube. It has the great advantage that at all times during the operation of the apparatus the voltage across the tube is known. Further details in connection with such an instrument will be found in the article by Montford Morrison to which reference has already been made.

Voltage by the Seeman Spectograph

20A. It is not possible to explain the principle utilized in this method of measuring a high voltage until something has been said about the nature of x-rays. The explanation, accordingly, must be deferred until we come to Chapter IX.

Capacity of an X-Ray Outfit

21. It is important for the reader to realize that the transformer is a means of supplying electrical energy to the x-ray tube. Now the actual amount of electrical energy supplied any portion of an electric circuit depends on three quantities; (1) the voltage, (2) the current, (3) the time.* Since the time factor is so readily taken care of, usually we consider the energy supplied per second, or what is known as *the power,* which obviously, then, depends on the voltage

* When alternating current is supplied a portion of a circuit containing inductance (see Section 31) the energy depends also on another quantity called the power factor. The amount of energy is still, however, proportional to the product volts-amperes-time.

and the current. [Compare the power available from a water-fall which depends on (1) the head of water, (2) the quantity of water coming over the falls per second. One million gallons falling each second from a height of 50 feet represent the same power as half a million gallons from a height of 100 feet.] To be more definite, when a current of 1 ampere is flowing in a portion of a circuit under a potential difference of 1 volt, the power is 1 volt-ampere or 1 watt. (746 watts = 1 horse power.) If 50 amperes flow under a potential difference of 110 volts, the power is 50×110 or 5500 watts. An electric toaster consuming 550 watts when operated on 110 volts has a current of 5 amperes flowing through it. When, therefore, the voltage used to drive 10 milliamperes through an x-ray tube is 20,000 volts, the power supplied the tube is proportional to $\frac{10}{1000} \times 20{,}000$ or 200 watts. The product does not give the exact value of the power in watts because although the current may be the correct average value, the voltage value in general is not the average, but probably the maximum (crest) value during a half cycle. Generally speaking, however, *we may compare the amounts of energy supplied a tube each second under different conditions by comparing the products of the effective crest voltages between its terminals times the currents flowing through it.*

Now the so-called "capacity" of an outfit refers to the maximum energy per second it is capable of supplying an x-ray tube. (The word "capacity" is not a very happy one, as in electrical science capacity has a very definite and distinctly different meaning; see Section 33.) It is usually expressed by giving the value of the maximum current which can be supplied a tube, under a specified "back-up." For example, in advertising literature one finds statements such as the following. A certain unit is "capable of energizing the 30 ma. 5″ Coolidge Tube"; the output of another is "rated at 250 ma. at 6″ back-up between points." Such

statements do not mean that the transformer may not be able to maintain a much higher voltage across a tube than the one stated. For example, in connection with the second of these outfits, the catalogue states further that "the *maximum* spark gap between points is 12 inches." Should higher voltages (than those corresponding to a 6″ gap) be utilized, a correspondingly smaller current would be supplied, because, once more, the power supplied depends on both the current and the voltage and, in this case, cannot exceed an amount proportional to the product (250 ma. × voltage corresponding to a 6″ gap between points). Occasionally one sees advertised a machine capable of giving, say, a 20″ spark, with no mention of the current. It should be evident that such a statement does not give all the necessary information, unless indeed, it is assumed that at such a voltage only very small milliamperages will be used.

22. The capacity of an x-ray unit is sometimes expressed in terms of the maximum power which may safely be supplied the primary of the high tension transformer. For example, a machine is sometimes advertised as having a capacity of 5 kw. (5 kilowatts = 5000 watts). This means that, if operated on 220 volts, primary currents as high as $\frac{5000}{220}$ or over 22 amperes may be utilized.* Since there is very little loss of energy in a good transformer, a 5 kw. unit can deliver nearly that same amount on the high tension side. It does not give, however, any information regarding the value of the highest voltage which may be generated since, as noted in Section 7, this depends on the ratio of the number of turns of the secondary coil to that of the primary.

23. In passing we may note that, quite apart from the capacity of the high voltage generating outfit, an x-ray *tube* has a maximum capacity. The 7″ Coolidge tube, for ex-

* Because of the power factor, the current might be much more than 22 amperes.

ample, is capable of carrying continuously about 1 kilowatt. Later, in discussing the action of the gas and the Coolidge tubes, details in connection with this question will be considered, but it is well to note here that it is again simply a question of how much energy per second it is safe to supply the tube.

Control of Back-up

24. In Section 21 reference was made to a machine with a capacity of 250 ma. at 6″ back-up, capable also of generat-

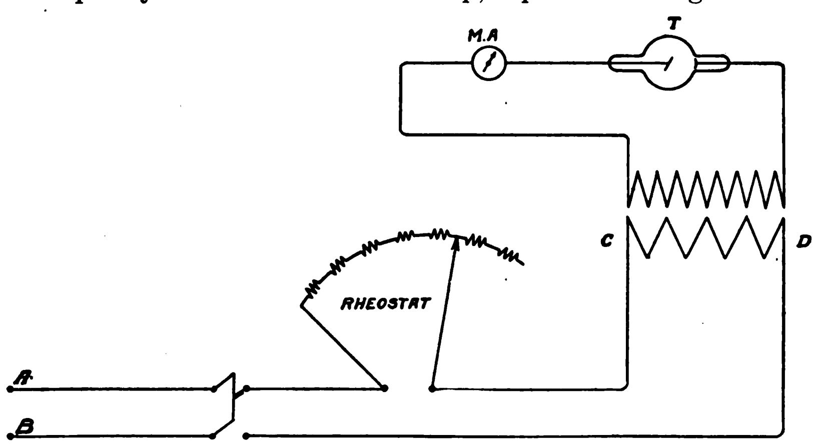

Fig. 25.—Connections for simple rheostat control of high tension voltage.

ing a maximum voltage corresponding to a 12″ gap. With this machine, as with all others, there is evidently a range over which different voltages may be utilized. How then, we next ask, is an operator able to alter the voltage available for the tube circuit? Three different means are utilized: (1) the rheostat, (2) primary convolutions, (3) the auto-transformer.

(1) **The Rheostat:** Reference has been made already to the use of the rheostat. One or two further points should be noted. Whenever a current has to flow against resistance, heat results (compare motion against friction) and

there is a certain loss of power. Moreover, since voltage is necessary to cause the flow of a current against resistance, *there is always a drop in voltage along a line containing resistance.* The magnitude of this voltage drop depends both on the current and the resistance—the greater each of them, the greater the drop. It follows, therefore, that if, at the main leads A and B (Figure 25), there is a supply of say 110 volts, the voltage across C and D, the terminals of the primary of the high tension transformer is less than 110 by an amount which depends on the resistance utilized in the rheostat and the current strength. In the case of the gas bulb this has a decided advantage over the auto-transformer control (see below). Suppose the resistance of a gas bulb T (Figure 25) suddenly lowers. (For reasons to be given later this may happen.) This means that the high secondary voltage at once causes a greater current in the tube circuit, and consequently, automatically, a greater current flows through the primary (to supply the necessary energy). Since, however, a rheostat is in the primary circuit, *this current increase means an increase in the voltage drop through the rheostat and, therefore, the voltage applied to the primary of the transformer lowers.* As a result of this, the high tension voltage will lower also, hence the tube current will lower again. In this way a rheostat acts as a kind of safety valve preventing a sudden increase of current beyond the capacity of the outfit. This is not so in the case of the auto-transformer.

(2) **Convolutions**: In some units the rheostat is supplemented by an additional control in the form of what are called convolutions. This simply means that the primary coil is wound in sections, so that different numbers of turns in the primary may be utilized. For example, in Figure 26, it is evident that by using terminals A and C, sections 1 and 2 of the transformer would be utilized; by using A and D, sections 1, 2 and 3 would be utilized, and so on. By such means the ratio between the number of turns of the

primary and that of the secondary may be altered by steps and in this way the maximum high tension voltage changed by corresponding amounts. In one catalogue the writer has seen a machine advertised with convolutions so arranged that voltages of 25, 45, 65, 80 and 100 thousand may be obtained. By using a rheostat on the line in the usual way a finer control of high tension voltages is possible and intermediate values may readily be obtained.

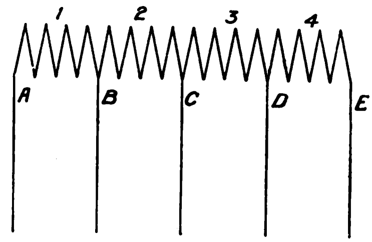

FIG. 26.—Representing four primary convolutions.

(3) **The Auto-Transformer**: This is practically a transformer with only the primary winding, or one where the same coil serves both as primary and secondary. Suppose (Figure 27) AB represents such a coil, with the usual iron core not shown. Then, if 110 volts A.C. are applied to the coil across AB, between the end B and some intermediate point C, there will be a voltage whose magnitude bears the same relation to 110 as the number of turns between B and C is to the total number of turns between A and B. If, therefore, C is a sliding contact, any voltage between 0 and 110 may be obtained by altering the position of C. (If the coil is extended as indicated by the dotted lines it is possible to obtain voltages higher than 110.) When, therefore, an auto-transformer control is used in an x-ray outfit, connections are made as illustrated in Figure 28. On closing x-ray Switch II, 110 (or 220) volts are applied across

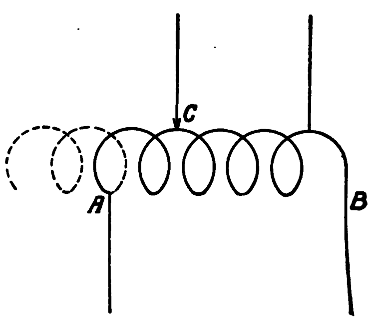

FIG. 27.—Simple auto-transformer connections.

the auto-transformer; a different voltage, whose magnitude depends on the position of the variable contact C, and is equal to

$$100 \times \frac{\text{number of turns in BC}}{\text{number of turns in AB}}$$

is at once applied to the primary of the high tension transformer, and in the usual way the induced high voltage causes a current through the tube circuit.

A comparison of the action of the auto-transformer with the rheostat may be obtained best by imagining again that the resistance of the tube suddenly lowers. In this case

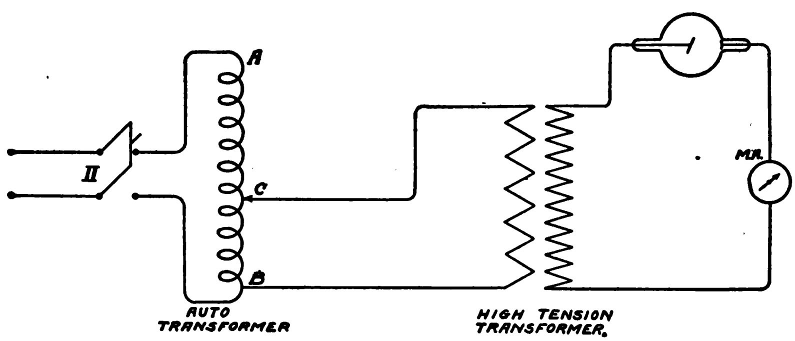

Fig. 28.—Connections for simple auto-transformer control of high tension voltage.

the high tension voltage at once causes a greater tube current; automatically the primary supplies more power (a greater current), while a greater current must also be supplied the auto-transformer. In this case, however, the voltage applied to the *primary* (that is, the voltage between A and B) does not lower. Consequently, the high tension voltage does not lower and it is quite possible that the suddenly lowering of tube resistance may result in current values increasing far beyond those safe for the apparatus, with consequent damage. Accordingly, whenever there is danger of the tube resistance lowering (as in the gas bulb), the auto-transformer control is not desirable. It may, however, be used in conjunction with a rheostat.

In Figures 29 and 75 both auto-transformer and rheostat controls may be seen on the same switchboards.

In the case of a Coolidge tube, as will be seen later, no sudden lowering of tube resistance is possible, and the auto-transformer may be used with advantage. With it, for any given position of the variable contact C, a constant voltage

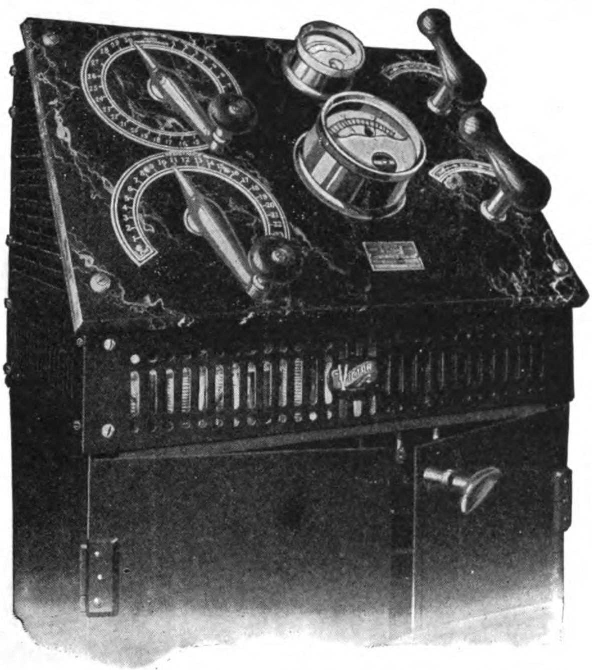

Fig. 29.—Photograph of control stand, showing both auto-transformer and rheostat control arms (Victor Electric Corporation).

is applied to the primary of the high tension transformer. The high tension voltage, therefore, has a constant value, an important consideration where x-rays are used for treatment. In the case of the auto-transformer, moreover, there is not the loss of power noted above in the use of a rheostat. Finally, to quote from literature of the General Electric Company, Schenectady, N. Y., "in diagnostic work it has been found that it is almost impossible to obtain

duplication of results when a series resistance control is employed for this purpose. We recommend that an auto-transformer be used for control for all diagnostic work and resistance control for therapeutic work." (This remark refers to the Coolidge Tube.)

Circuit Breaker

25. This is a device added so that the circuit may be automatically broken should, for any reason, the current strength (the load) exceed the capacity of the outfit. This might happen, for example, in the case of a gas tube and auto-transformer control, or again because of the accidental short-circuiting of the high tension circuit. The principle underlying the use of many circuit breakers is briefly the following. In the circuit is placed an electro-magnet which exerts an attraction on a piece of soft iron near it. When the current exceeds a certain strength the attraction is sufficient to move the soft iron and so cause the opening of a switch in mechanical connection with it.

Rotary Converter: Motor-Generator

26. From the description of the interrupterless transformer which has been given, it should be evident that an alternating current is necessary. Supposing only a supply of direct current is available, what then? In that case, some kind of additional apparatus for obtaining alternating current is necessary. One may use a *motor-generator* set, that is, a combination of a motor, in this case to run on D.C. (direct current) and a generator which is rotated by the motor and "generates" the desired A.C. One may also use a *rotary converter,* which is a single machine by means of which D.C. may be supplied at one side, and A.C. taken off at the other (or vice versa). The general principles of the high tension outfit for D.C. supply are otherwise the

same as described above, except that when a rotary converter is used, a synchronous motor is not necessary. The rectifying disc is turned by the converter at the proper speed because it supplies the alternating current delivered to the transformer.

27. Another way in which a source of D.C. may be utilized for obtaining high voltages, is found in the use of the induction coil, the second of the two methods noted in Section 1. Although in North America the transformer is used almost to the exclusion of the coil, the latter is by no means obsolete, and a detailed consideration of the principles underlying its construction and use is desirable.

References:

1. Standardization Rules of American Institute of Electrical Engineers.
2. Coolidge and Kearsley, *Amer. Jour. of Roent.*, IX, 77, 1922.
3. Fortescue and Chubb, *American Institute of Electrical Engineers*, XXXII, 739, 1913.
4. Rieber, *Amer. Jour. of Roent.*, IX, 371, 1922.

CHAPTER III

THE INDUCTION COIL

28. In the coil, as in the transformer, the principle of electro-magnetic induction is utilized. Indeed the induction coil is a modified form of transformer. A direct current flowing through a primary coil wrapped about an iron core is regularly made and broken. The magnetic lines of force, therefore, which traverse the iron core, regularly appear and disappear, and, in consequence, there are induced electro-motive forces (E.M.F.) in a secondary coil wrapped over the primary. On "make" of the primary current the induced high voltage is in one sense, on "break" in the opposite. By making the number of turns of the secondary many times greater than that of the primary, very high voltages may be obtained just as in the case of the transformer.

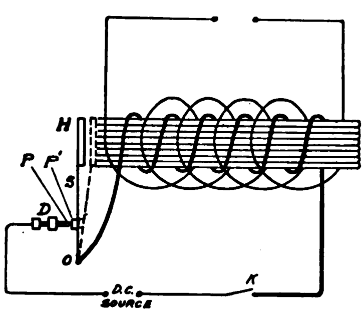

FIG. 30.—Connections of Induction Coil, with Hammer break, without condenser.

29. To make and break the current regularly what is called an *interrupter* is used. There are three types of these in general use, (a) the hammer, (b) the mercury jet, (c) the electrolytic or Wehnelt. Some details in connection with each of these will be noted. First of all, however, the action of the coil will be discussed with reference to one fitted with a hammer break, the kind in general use on small coils. Figure 30 represents a primary coil wrapped

about a bundle of iron rods which constitute the (open) core of this type of transformer. The coil is supplied with current from D.C. source (such as a number of storage batteries, or, in the case of large coils, the supply terminals joined to a direct current generator), connections being made as shown in the diagram. P represents a contact point made of a metal such as platinum, attached to the end of a screw passing through a rigid support D. H is a piece of soft iron (the hammer) at the end of a steel spring S, the other end of which is rigidly fastened to O. Normally (that is, when no current is flowing) the platinum point P touches a small piece of platinum P′ attached to the spring. Now suppose the switch K is closed. A current then flows because there is a complete circuit from one terminal of the source through the coil to O to P′ to P and back to the other terminal of the source. This current magnetizes the iron core, which accordingly attracts the hammer, pulling it to the dotted position. This movement of the hammer breaks the contact between P and P′; the current, therefore, ceases to flow; the core loses its magnetism; the hammer, being no longer attracted, flies back and in so doing brings the contact points P and P′ together again, and so closes the circuit. The action is then repeated. As long, therefore, as K is left closed, with such a device the primary current is *automatically* made and broken. Hence, if a secondary coil is wrapped about the primary, there will be induced in it a high electro-motive force, in one sense on make, in the opposite on break.

30. Now what about the *magnitude* of the high voltage which may be obtained in this way, and in particular, what about the relative magnitude of that obtained on make as compared with break? To understand the answer to these questions it is necessary to remember that the magnitude of any induced E.M.F. (Section 5) depends on both the total change in the number of lines linked with the circuit and the time in which the change takes place. By

having a strongly magnetized core and many turns in the secondary, therefore, very high voltages may be obtained *provided the time of either make or break is very short.* Now as a matter of fact in building a good coil, one of the chief aims of the maker is to make the time of break so many times less than that of make that the induced voltages obtained on make may almost be neglected in comparison with that of break. In other words, a good coil is able to deliver a current which is practically uni-directional through a tube. To explain why the time of break is so much shorter involves a consideration of one or two further points.

INDUCTANCE

31. The effect of having a large inductance in the circuit must be clearly understood. Suppose a simple circuit contains a battery or some D.C. supply and an electro-magnet. When a current is flowing a large number of magnetic lines are linked with the turns of the electro-magnet, and we say the circuit has a high *inductance.* Practically the inductance is measured by the number of lines linked with the circuit (due regard being taken of the number of turns) when a current of one ampere is flowing through the coil. Consider now what happens during the short time in which the current rises from zero to its final steady value. As the current increases, more and more lines are being introduced and so there is continually a change in the number linked with the turns of the electro-magnet. By the principle of electro-magnetic induction, therefore, there will be an induced E.M.F. in this coil itself. This is a self-induced E.M.F. or better the E.M.F. of inductance. Now the direction of any induced E.M.F. is always such as to oppose the change causing it. In this case, therefore, the effect of inductance is to set up a voltage (E.M.F.) *opposed* to the applied voltage (of the battery) and in consequence, to cause a delay in the rise of the current to its

steady value. In other words, the effect of inductance in a D.C. circuit is to prolong the time it takes for the current to rise to its steady value. Similarly, if a circuit containing inductance is broken, during the time in which the current is falling to its zero value, there is continually a change (in this case a decrease) in the number of lines linked with the circuit, and again an E.M.F. due to inductance. Again, the inductance E.M.F. opposes the change and unless the circuit is broken in a special way (see below) it prolongs the time of break for the following reason. The actual magnitude of the inductance E.M.F. is generally so great that when a circuit is broken it results in a spark jumping across the gap where the break is made. For a short time, therefore, a conducting path is established at the contacts. Anyone who has ever broken a circuit containing an electro-magnet cannot fail to have observed the spark which takes place, on break, at the switch used to break the circuit. *To sum up, then, with a large inductance in a circuit, the time of make is prolonged, while unless special precautions are taken, at break a spark will jump the break gap and so prolong the time of break.*

Now, obviously, once a circuit is closed, we have no further control over it. The time of rise depends on the amount of inductance and the general arrangement of the circuit. When a circuit is broken, however, the time of break depends on the mechanical means used to break the circuit. If, for example, it is broken by firing a bullet and so breaking a wire (this has actually been done) the time of break is very short, so short, indeed, that the two parts where the break occurs are separated so quickly that there is no chance for the spark to jump across.

32. Now let us apply this idea of the last section to the arrangement of Figure 30. In this case the hammer is pulled back by the elasticity of the spring, and the time of break is not short enough to prevent a spark jumping across the contact points. The time of break, therefore,

(as well as make) is not sufficiently short to give a high voltage, and such an arrangement would be of little use for a practical coil. Moreover, a large percentage of the energy which is stored up in the magnetic field (almost the whole of which in an ideal coil is transformed into the energy of the induced current in the secondary coil) appears in the spark or possibly the arc, which occurs at the contact points.

33. To secure the necessary short time of break a *condenser* must be placed across the contact points P and P′, as illustrated in Figure 31. The form of condenser used consists of two sets of tin foil, each of many sheets, separated by some dielectric, often paraffined sheets of paper. This arrangement of conductors has what is technically called a high *capacity* (here the word is used in its accurate scientific sense) by which it is meant that, before the potential difference (voltage) between the two sets of plates can rise to values great enough to cause a spark discharge to take place through the paper, an enormous quantity of electricity must be on each set (positive on one, negative on the other). What, now, is the effect of placing a condenser across the contact points? Briefly it is somewhat as follows. When the switch K is closed, and the primary current begins to rise, a certain quantity of electricity will flow into the condenser, one set of plates becoming positively charged, the other negatively. Consequently, the first effect of the condenser is to delay still further the time of make. When the primary current has

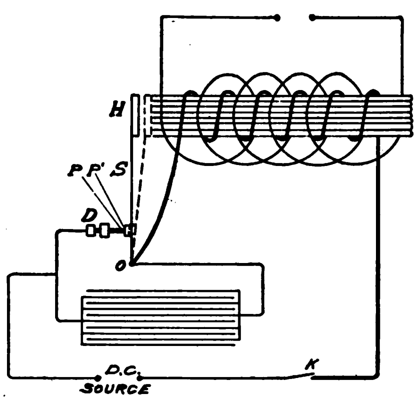

FIG. 31.—Connections of Induction Coil, with Hammer break, and condenser.

magnetized the iron core sufficiently the hammer is attracted and the points separate. Because of the condenser, however (and here we have a second advantage), little sparking occurs at the points, for the E.M.F. of inductance causes a further charging of the condenser. Arcing, therefore, does not prolong the time of break, and for that reason there is much less loss of energy due to this cause. (The energy corresponding to the charging of the condenser is regained when the condenser immediately discharges back through the primary coil.)

To sum up, then, a condenser lengthens the time of make, shortens the time of break and prevents much of the sparking and arcing at the contact points. *It is possible, therefore, by using such a device to build up a coil whose high tension voltage on break is enormously greater than on make.* There is, however, always some induced voltage at make, and herein lies one of the drawbacks of the coil. Some means must be utilized to get rid of the current due to this *reverse,* or, as it is generally called, *inverse* voltage. Such means are discussed in Section 38.

34. In actual practice the condenser has to be adjusted to suit the particular primary coil utilized, because the maximum high voltage generated depends greatly on the actual capacity of the condenser. It has been shown, for example, that by changing nothing but the capacity the maximum potential of a given coil could be changed as much as two and one-half times. The same coil, moreover, is not adapted for use under a variety of conditions. To quote from Knox, the eminent English radiologist, "it is far better to have several coils built for special purposes than to endeavour to achieve with one coil the same results under varying conditions of interrupter."

In larger coils operated by means of a hammer break, the interrupter is often on a separate mounting, a small electro-magnet being used to attract the hammer. Figure 32 is an illustration of such an interrupter.

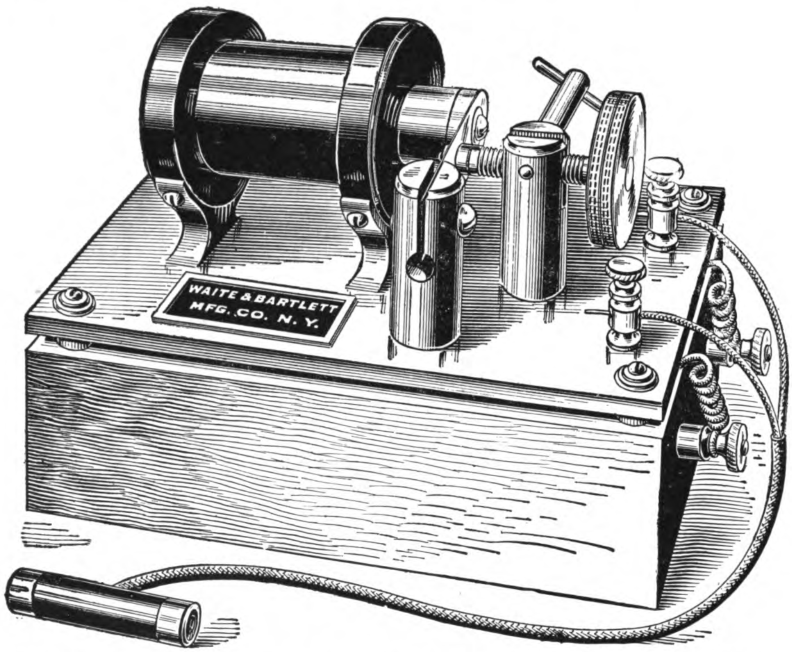

FIG. 32.—A Hammer break for induction coil (Waite and Bartlett Co.).

FARADIC CURRENTS—FARADISATION

35. Figure 33 is a reproduction of an actual photograph (due to Salomonson) of a record of the primary current during a single make and break. The comparatively slow rise to a maximum followed by a quick drop is clearly shown in the illustration.

If records are made of the current in the secondary (when an x-ray tube is in the circuit) as well as of the secondary voltage, curves somewhat similar to those shown in Figure 34 are obtained. In (b) the fairly large inverse voltage is clearly shown, while in (a) the resulting slight inverse current can be detected. The exact nature of these curves will vary with the conditions and in general they are not quite so simple as those represented in Figure 34. These

graphs, however, represent correctly the general nature of what are called *faradic* currents. In so-called *faradisation*

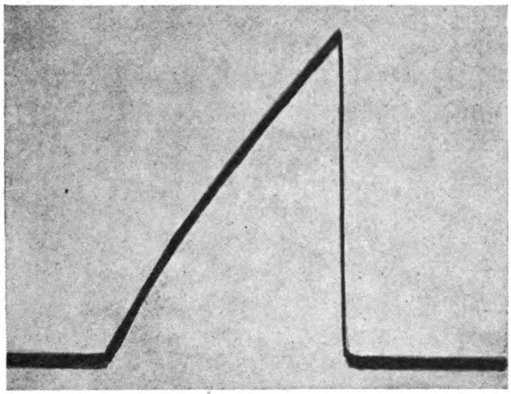

FIG. 33.—Actual photograph of rise and abrupt fall of primary current in induction coil (Salomonson).

use is made of these currents. It will be seen that they are characterized by sudden abrupt changes of current and

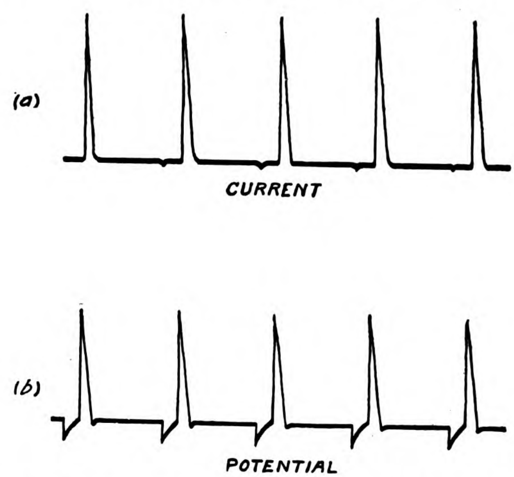

FIG. 34.—Graphical representation of current and of voltage changes in secondary of induction coil.

of potential, markedly different from the smooth, gradual changes of sinusoidal currents. The *secondary faradic,* as

its name implies, refers to the use of the secondary of a coil. In the *primary faradic* use is made of the E.M.F. of inductance which has been discussed in Section 31. By placing across the contact points leads connected to the patient, on each break, a sudden stimulus is received.

The Mercury Break Interrupter

36. For small coils, or those on which heavy demands are not to be made, the hammer break is fairly satisfactory.

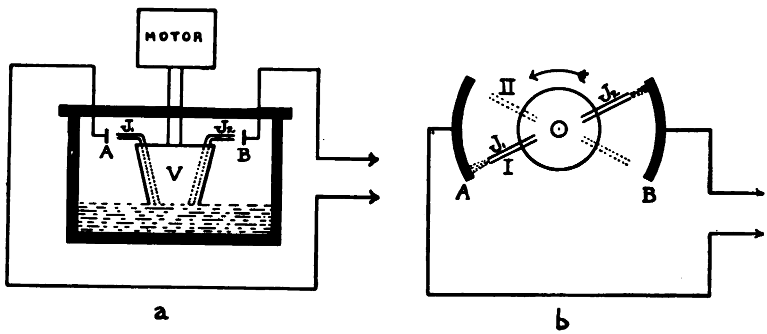

FIG. 35.—To illustrate action of mercury interrupter, (a) Side view, (b) top view.

With coils which are to be used for heavy radiographic work, the hammer break is of little use. The excessive sparking, accompanied by disintegration of the contact points, makes such a break very unsatisfactory. Large coils, therefore, are operated by using either a mercury or an electrolytic interrupter. The principle utilized in the construction of the former of these will be clear from the following brief description of one type in common use. By means of a motor (Figure 35, a, side view; b, top view) a vessel V whose lower portion dips in mercury can be rapidly rotated. As a result of the rotation mercury rises until it is forced out of the tubes J_1 and J_2 at the top of the vessel. If the tubes are in the position shown in Figure 35b, the jets

of mercury on leaving the tubes strike two metal pieces A and B which take the place of the contact points of the hammer break. In other words, the interrupter is placed directly in the primary circuit and current can only flow when there is electrical connection between A and B. This will be the case when the jets are anywhere between positions I and II of Figure 35b. As soon, however, as the vessel has rotated past position I, contact is broken. As V rotates, therefore, the current is regularly interrupted, the number of interruptions depending on the speed at which the motor is rotated. The rotating vessel, together with the contact pieces A and B and the supply of mercury, are all enclosed in a containing vessel in which the air is replaced either by a liquid dielectric such as paraffin or by ordinary illuminating gas from the supply mains. In the latter case care must be exercised that no air is left in the apparatus, otherwise an explosion may occur.

From the nature of this break it should be clear that the frequency (the number of makes and breaks per second) may be varied over a wide range by simply regulating the speed of the motor. Frequencies as high as 200 per second may be obtained. By way of comparison it may be stated that although in the case of the hammer break the frequency may also reach this maximum value, it is often as low as 25 or 30 per second.

Mercury interrupters often require a fair amount of cleaning and frequent overhauling, although the writer has seen one type advertised (the so-called constant interrupter) which, it is claimed, requires "no more attention than an interrupterless apparatus."

THE WEHNELT ELECTROLYTIC INTERRUPTER

37. To utilize this type of interrupter, a vessel containing a 20 per cent solution of dilute H_2SO_4 (specific gravity 1.2) is inserted in the primary circuit. The positive elec-

trode (the anode) is a platinum point P (Figure 36), the negative electrode (the cathode), a large lead plate L (note also Figure 37). With such a device, when the primary circuit is closed in the usual way, the current is regularly and rapidly interrupted at the platinum point,

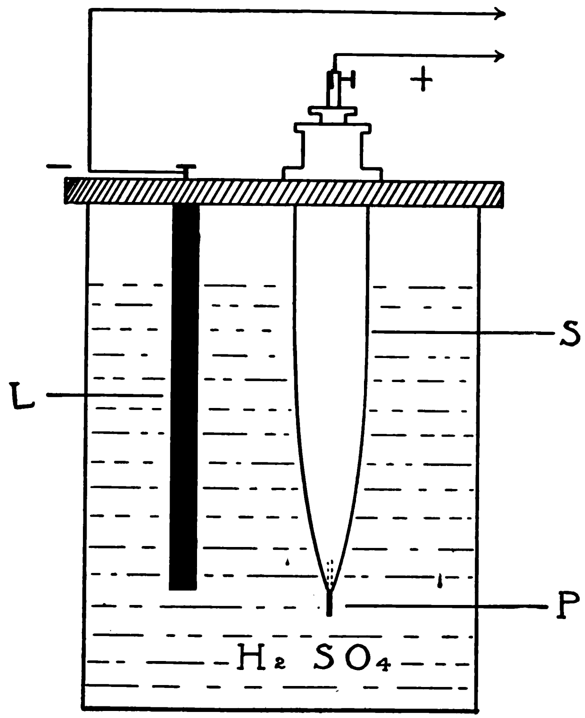

FIG. 36.—Wehnelt Interrupter.

provided current conditions are within certain limits. The amperage, for example, should not be much below 10 nor much above 40 amperes, while with voltages across the terminals exceeding 80 to 120 the interrupter will not work. Potential differences of the order of 60 volts are normal.

It is difficult to state with certainty the exact nature of the action of this type of interrupter. It is somewhat as follows: When the current begins to flow, the formation

of gas bubbles about the platinum point introduces an insulating layer which soon breaks the circuit; the E.M.F. of inductance causes a spark to jump the gap, thus exploding the gases and closing the circuit once more. In some such way a periodic opening and closing of the circuit takes place. But the action is complicated, the frequency depending on the amount of inductance and of capacity in the circuit, the temperature and the concentration of the acid, and the size of the platinum point. By means of an insulating sheath S the extent to which the platinum point is exposed to the acid can be altered and in this way the interrupter regulated. Values of the frequency as high as 1500 or 2000 per second may be obtained, while even with heavy currents the frequency may not go below 200 per second. "With a suitable current the anode is normally surrounded by a violet light, and the interruptions are of an explosive and almost deafening character." (Kaye.) Silencers, however, are now added, thus eliminating to some extent the latter undesirable feature.

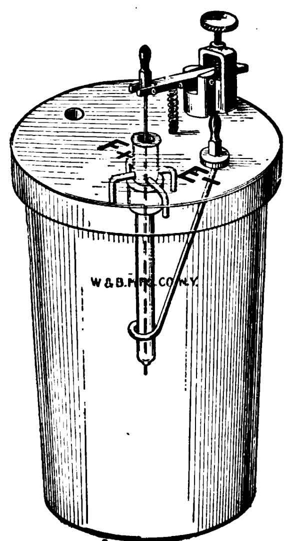

FIG. 37.—Wehnelt Interrupter (Waite and Bartlett Co.).

The electrolytic interrupter has the advantage that no condenser is necessary, but the disadvantage that considerable inverse is present.

SUPPRESSION OF INVERSE OR REVERSE CURRENT

38. As already noted it is highly undesirable to have any reverse current passing through an x-ray bulb. The reasons for this will be more apparent later; here we may simply

state that inverse current (1) gives rise to x-rays from parts of a tube other than the target; (2) increases the possibility of a tube puncture and, apart from puncture, shortens its useful life; (3) gives rise to erroneous and consequently misleading readings of the milliamperage in the tube circuit. (Regarding (3) it should be evident that, since milliamperemeters are *direct* current instruments, the presence of a reverse current will make the reading on

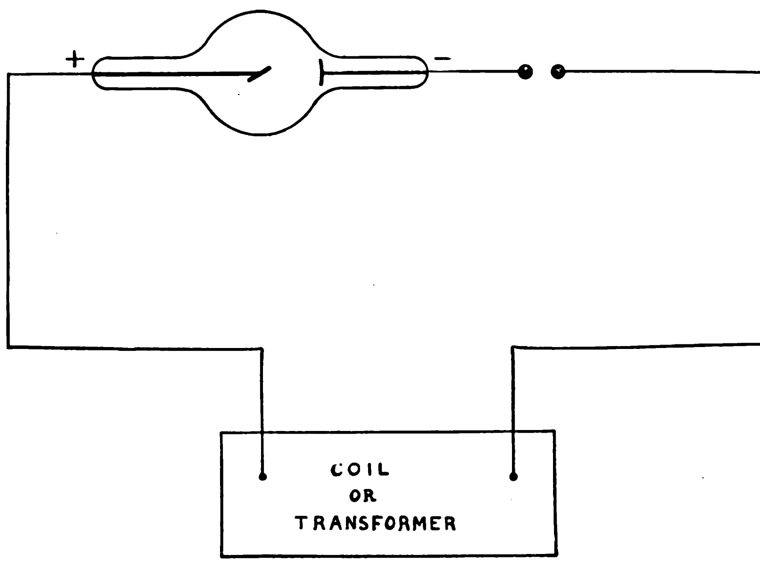

FIG. 38.—Arrangement of spark gap to suppress inverse.

the instrument less than that corresponding to the current passing in the right direction.) When, therefore, coils are used as the source of high potential, certain rectifying means are used to suppress any inverse which may be present. A brief reference will be made to a few of these:

(1) **The Spark-Gap**: Any kind of spark-gap inserted in series with the x-ray tube, as in Figure 38, is effective provided the voltage necessary to cause a spark to jump the gap has about the same magnitude as the inverse. Obviously a voltage less than that corresponding to the

spark length can cause no current in the tube circuit. This method entails a considerable loss of energy and would be useless for cases where the magnitude of the inverse voltage approached that of the direct.

(2) **The Point-Plane Gap**: An improvement of method (1) consists in using a point-plane spark-gap. This is more effective because a discharge crosses such a gap more readily when the point is positive than when it is negative.

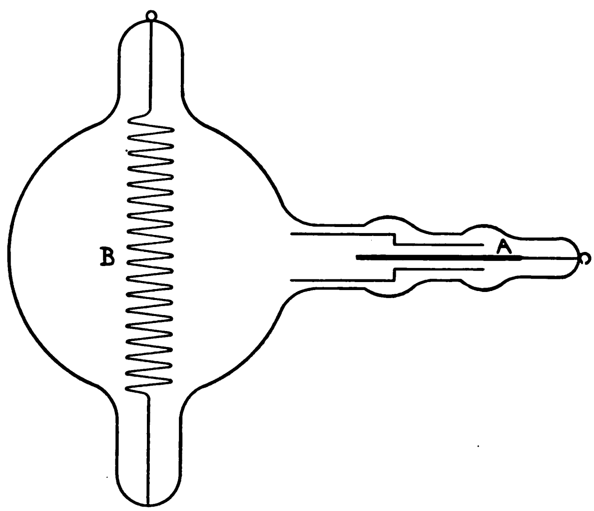

FIG. 39.—A valve tube.

Such a gap, therefore, should be connected in series, just as in Figure 38, care being taken that, for the current in the right direction, the point is joined to the negative terminal (the cathode) of the tube.

(3) **Valve Tubes—Old Type**: Possibly the rectifier most frequently used with coils is the valve tube. The older type consists essentially of a vessel (Figure 39) from which the air has been *partially* removed, and which contains two electrodes, one, A, enclosed in a side arm, the other, B, extending into the central part of the valve tube so that, unlike the first, it is quite *unrestricted*. The efficiency of

this kind of valve depends on the fact that, with the gas pressure in the vessel within proper limits, a restricted electrode will function practically only as an anode (*i.e.*, a positive terminal). Such a valve, therefore, is placed in series with the x-ray bulb again, just as in Figure 38, care being exercised that the restricted electrode is joined to the negative terminal of the tube.

(4) **Valve Tube—New Type—The Kenotron.** A much more satisfactory type is found in the *Kenotron,* reference to which will be made in connection with the Coolidge Tube (Section 64). Here we may note that the principle utilized is exactly the same as that underlying the valves used so extensively in "Radio" work.

(5) Other mechanical rectifiers have been used in connection with induction coils, at least one of which differs little in principle from the rectifier utilized in the interrupterless transformer. Little would be gained, however, by extending our discussion on this subject.

The Coil Versus the Transformer

39. Although the coil for heavy x-ray work is used so little in the United States and Canada that one can with difficulty find it mentioned in advertising literature, it should not be overlooked that in England and on the continent the coil is by no means obsolete. In the recently (November, 1922) opened x-ray department of the Manchester Royal Infirmary, for example, coils have been retained in the treatment room, although high tension transformers form the major portion of this part of the equipment. Moreover, in the extensive volume on radiography by Knox (Vol. I, 1917) radiographs are shown which indicate, if anything, superior work in the case of the coil. Further evidence that much is to be said for the coil is found in the report in the *Electrician* (March, 1920) of a discussion on this whole question by eminent English radi-

ologists, in conjunction with electrical engineers. It must be remembered that the coil generates a high voltage which attains to its maximum value and drops to zero in a small fraction of the time between successive breaks, whereas in the case of the transformer the high voltage is applied for often a considerable fraction of a half-cycle, that is, for a considerable fraction of the total time between successive impulses. This gives the coil an advantage within the limits of its capacity. But, for heavy work, the advantages are all in favor of the transformer, while the freedom from interrupter troubles is a tremendous gain.

In treatment where a high peak voltage is required, with low milliamperage, the coil has been used with much success. One eminent radiologist, Dr. E. Reginald Morton of London, England, informs the writer that with a symmetrical coil apparatus excellent work has been done. On the other hand, in some tests made at the General Electric Co., Coolidge and Kearsley have shown that some high voltage Coolidge tubes which operated smoothly on voltages as high as 300,000 generated by an interrupterless machine, failed to do so above 140,000 on a coil.

CHAPTER IV

THE ORIGIN OF X-RAYS

40. In the gas bulb a current passes through the rarefied gas in the bulb; in the Coolidge tube a current passes, although the vacuum is nearly as perfect as modern means of exhaustion can make it. Before the action of either can be understood, it is necessary to consider somewhat in detail the whole question of the passage of electricity through a gas. At the outset it is well to recall certain fundamental electrical ideas.

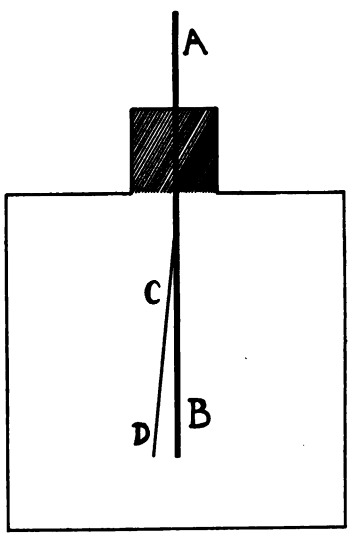

FIG. 40.—A simple electroscope.

Any two bodies when rubbed together (so that their surfaces may come into close contact) become electrified, one positively, the other negatively. By positive we mean simply a charge of electricity similar to that on a glass rod which has been rubbed on silk; by negative, a charge similar to that on an ebonite rod rubbed on fur, or to that on a piece of sealing wax rubbed on wool.

A body with a positive charge repels a second body similarly charged but attracts a negatively charged one.

To study many things in connection with electrified bodies one frequently uses the *gold leaf electroscope.* In a simple but useful form this consists of a metal rod AB (Figure 40) *insulated* from the supporting vessel, attached

to which is a piece of light metallic leaf CD (*gold* leaf is not necessary). If the rod and leaf are given an electric charge, either positive or negative, the light leaf is deflected an amount proportional to the charge on the insulated system.

Ionization of a Gas

41. Suppose an electroscope, made with the most perfect insulation possible, is given a charge. If the deflection of

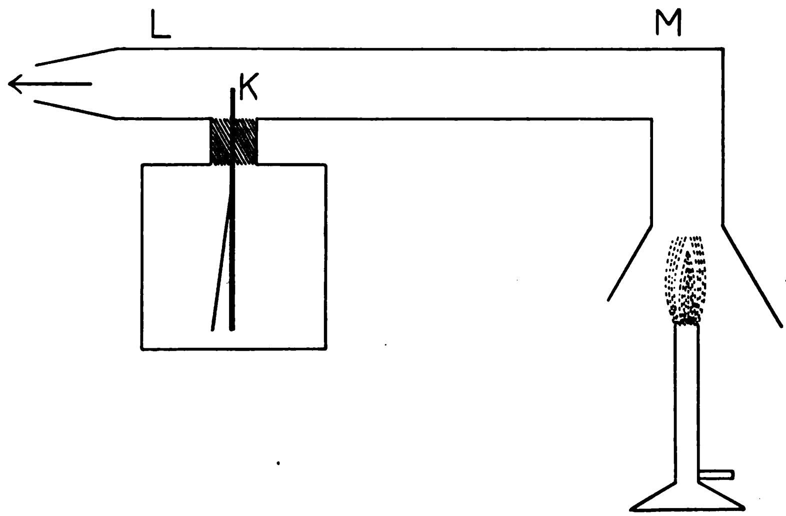

Fig. 41.—Ions from flame discharge electroscope.

the leaf is observed hour after hour it will be found that, although there is an extremely slight falling of the leaf the charge is retained even for days. We conclude, therefore, that while air is not a *perfect* insulator, at any rate it is an extremely poor conductor of electricity. (Evidence that air is not a perfect insulator has been given implicitly when it was pointed out that, once the voltage across two conductors exceeds a certain value, a spark jumps the gap between them.)

It is possible, however, to put air into a fairly good

conducting state. A simple experiment will illustrate one means of doing so. Suppose a lighted match is held near the projecting end of a charged electroscope. It will be found that in a few seconds the leaf has fallen and the electroscope is discharged. The air in the neighborhood of the electroscope has had its conductivity enormously increased by the presence of the flame. In other words, the flame is what we call an *ionizing agent,* causing marked

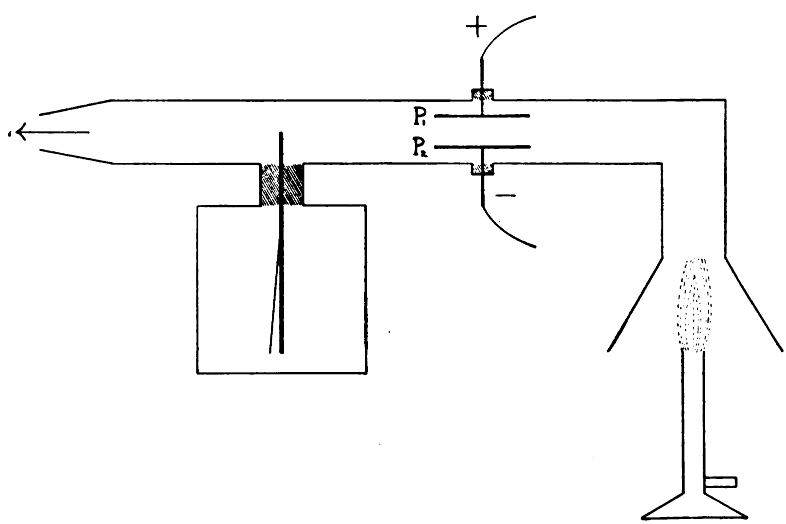

FIG. 42.—Ions from flame removed by electric field.

ionization of the air in its neighborhood. An explanation of the meaning of ionization can best be given with reference to one or two further experiments.

Suppose we have an arrangement of apparatus similar to that illustrated in Figure 41. In this case air from the neighborhood of a flame may be sucked through a tube LM, into which projects the top K of the insulated rod of a charged electroscope. With such an arrangement it will be found that as soon as the air from the flame is sucked along the pipe the electroscope begins to lose its charge.

Evidently air in the conducting state can be carried from place to place.

Imagine next, that the apparatus is altered so that the ionized air in its passage along the tube has to pass between two plates P_1 and P_2 (Figure 42), which are joined, one to the positive, the other to the negative terminal of an electrical machine or high voltage battery. It will now be found that, in spite of the suction through the tube, the electroscope *retains* its charge. In other words, the conducting air, after passing between the charged plates has lost its conductivity or is no longer ionized.

The removal of the conductivity by the charged plates (and many other experiments) suggests that air is made a conductor because of the formation by the flame of small electrified particles or *ions*. This provides a ready explanation of the discharge of the electroscope. If it is positively charged and ions are found near it, positive ions will be repelled, negative attracted. Each negative ion on reaching the insulated rod of the electroscope will annul some of the positive charge on it until finally the electroscope is completely discharged. Moreover, all the time the discharge is taking place *there is a stream of positive ions in one direction, negative in the opposite.* Such a stream of ions constitutes an electric current through the air.

Ions and Electrons

42. But, it is asked, what *are* ions? As a result of the work of the physicist in the last twenty or thirty years, the answer may be given with some confidence. It is now believed that an atom (of any element) consists of a core or nucleus, positively charged, together with a certain number of small negatively charged particles, called *electrons.* In spite of the attraction of positive for negative, the electrons do not "fall into" the nucleus, probably because of their planetary motion about it. (The earth for the same

reason does not fall into the sun.) The nucleus, which is responsible for practically the whole mass of the atom, has a different constitution for each atom; electrons, however, whose mass is about $\frac{1}{1800}$ of that of a hydrogen atom are identical in all atoms (see Section 46). The *number* of electrons, however, increases with the atomic weight of an element. For example, there is much evidence to indicate that the hydrogen atom has only 1 electron, helium 2, lithium 3, and so on until we reach heavier elements such as mercury with 80 electrons. It is now generally accepted that, with one or two exceptions, the number of electrons in an atom is equal to the number of the element when the elements are arranged in the order of increasing atomic weight. Putting it in another way, the so-called *atomic number* gives the charge on the nucleus in positive units.

Normally the negative charge on the electrons exactly neutralizes the positive charge on the nucleus, so that the atom in its ordinary state is electrically neutral. If, however, *by means of an ionizing agent such as a flame, an electron is removed from the parent atom, it should be evident that what is left will be a particle of atomic size, with an excess of positive electricity, or a positive ion.* The electron which has been removed may either remain "free" or attract to itself one or more neutral molecules, or atoms, thus forming what is called a negative ion.

Later we shall see that one of the most important properties of x-rays is their ability to ionize a gas.

(It should now be evident that, to account for the extremely slight conductivity of ordinary air, we must assume the existence in air at all times, of a few stray ions. In these ions, too, we find the explanation of the corona and the spark discharge. When an electric field becomes intense enough, the ions are moved along with such a high velocity that they ionize neutral atoms and molecules with which they collide. The ions formed by such collisions in

their turn are speeded up by the electric field and they too ionize other neutral atoms and molecules. In this way, once an electric field of a critical intensity has been reached, ionization increases so rapidly that a discharge is the result. In the case of a spark, the rapid multiplication of ions takes place along an almost continuous path between the charged conductors, whereas, with a corona discharge, the intense ionization is only in the region of the intense fields near pointed conductors [see again Section 17A].)

Conductivity of Air at Pressures Less Than Atmospheric

43. In this course we are interested particularly in the conductivity of air at pressures considerably less than atmospheric. Suppose that the terminals of an x-ray bulb or

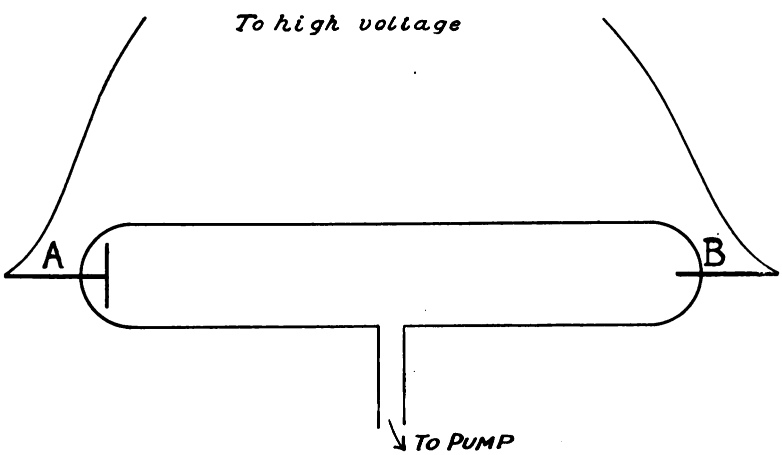

Fig. 43.—A simple vacuum tube.

any "vacuum" tube with electrodes A and B (Figure 43) is joined to an induction coil or a high tension transformer. Suppose, further, that the tube at the start contains atmospheric air and that the electrodes are at such a distance apart that no spark discharge can take place. If, now, by

means of an exhaust pump, the air is gradually removed from the tube, a stage will soon be reached at which a discharge passes readily—this stage being indicated by a line of luminosity which extends from one electrode to the other. As exhaustion proceeds the current passes more and more readily until a second stage is reached beyond which the current passes less readily, until finally, when a very high vacuum has been attained, the resistance is so great that the tube will not conduct at all. Some actual measurements (taken from Townsend's *Electricity in Gases*) are given in Table III. This table gives the voltages necessary to maintain a current of 10 ma. through a tube 3 cm. in diameter, with electrodes 11.5 cm. apart, at various pressures.* It will easily be seen that as the pressure lowers, at first a lower and lower voltage is required, but after a certain critical value has been reached, higher and higher voltages are necessary. Evidently, then, *the*

TABLE III

Pressure...	4 mm.	2.84	1.65	1.04	.66	.4	.29	.24	.17
Voltage...	650 volts	620	500	470	490	530	590	630	740

resistance of a vacuum tube or a gas x-ray bulb depends on the degree to which it has been exhausted. Moreover, after a certain critical pressure has been passed, it is more and more difficult to pass a given current through an exhausted tube. Technically, it is said that the tube becomes *harder and harder,* as the pressure gets lower and lower. The harder a gas x-ray tube is, therefore, the greater the voltage necessary to maintain a given current through it.

* Readers will recall that the pressure of a gas is frequently expressed in terms of the length of the column of mercury it will support. Atmospheric air, for example, will support a column of mercury which varies from day to day, but is in the neighborhood of 760 mm. In the experiment to which Table III has reference, an air pressure has been reached which supports a column of mercury only 17/100 mm. high.

THE APPEARANCE OF A VACUUM TUBE CARRYING A CURRENT

44. The appearance of a vacuum tube when conducting a current at low pressures is very beautiful, and has certain general characteristics which it is well to note. Initially, or very shortly after the gas has become conducting, a single sharp narrow streamer extends the length of the tube. As the pressure is reduced the band of light becomes wider and more and more diffuse until the whole tube is filled with luminosity. At still lower pressures (of the order of half a millimeter) the tube has a striking and very characteristic appearance: (1) Around the cathode is a thin luminous layer, A in Figure 44; (2) next is a sharply

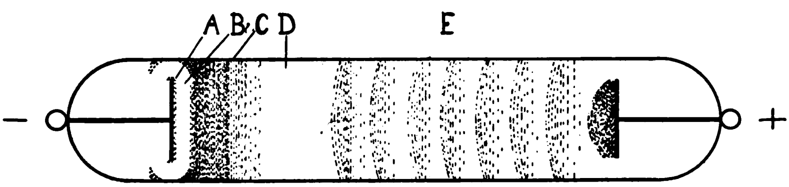

FIG. 44.—Typical appearance of vacuum tube at a certain pressure.

defined dark space B, followed by, (3) another luminous region C, then (4) a second ill-defined dark region D, and finally (5) a column of luminosity E, extending to the anode. At certain pressures this column is broken up into beautiful striations, that is, narrow regions alternately dark and light.

Most important of these regions is the sharply defined dark space, the Crookes' dark space, as it is called, or sometimes "the" dark space. With decreasing pressure, its width continues to increase, and is indeed a rough measure of the degree to which the tube has been exhausted. In the case of a gas x-ray tube the dark space should fill the whole tube. If, by any chance, an x-ray bulb presents the above appearance, that is, one with marked luminosity, the pressure is much too high and the tube must be

re-exhausted before it is of any use. In the case of a Coolidge tube, careless manipulation may result in the liberation of gas. If sufficient gas is present, this will be evident by the general luminosity filling the tube when a high voltage is applied. Again, re-exhaustion is the only remedy.

Cathode Rays

45. When exhaustion is extended beyond that giving rise to the above characteristic appearance, the dark space, as already noted, grows wider and wider until it finally fills practically the whole tube. This occurs at what we may call the x-ray vacuum, for the pressure has now been reduced * to about 1/100 mm., that is, to a value which is about the order of that in a gas x-ray bulb. At this pres-

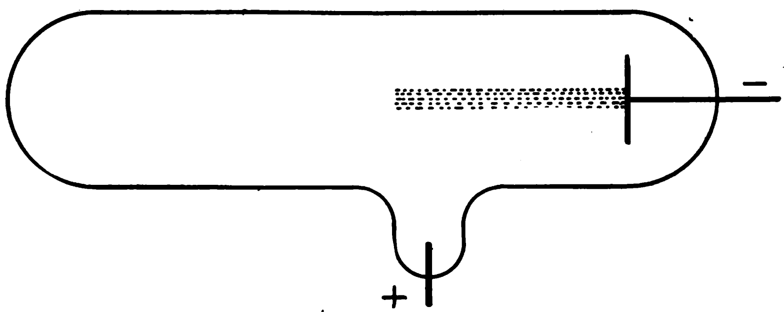

Fig. 45.—Cathode rays leave cathode normally.

sure a very faint beam of light proceeding *at right angles* to the cathode is frequently visible. Depending on conditions, this beam may be narrow, covering only a small portion of the face of the cathode, or it may cover nearly the whole of it; it may be extremely faint, or it may be well defined. (Often it is quite visible in a "soft" x-ray bulb.) The direction of this beam, moreover, is independent of the position of the anode. For example, in a tube of the shape illustrated in Figure 45, the beam is still

* We speak of raising the vacuum when we lower the pressure.

at right angles to the cathode, although the anode is in an arm at one side of the tube.

A second important appearance is characteristic of this stage. The walls of the tube, particularly at the end opposite the cathode, are seen to fluoresce with a light, frequently greenish, but whose color depends on the composition of the glass. That the fluorescent light has some connection with the faint streamers is readily shown by simply bringing one pole of a magnet near the cathode end of the tube. Both the faint beam of light and the position of the fluorescent light at the other end move simultaneously.

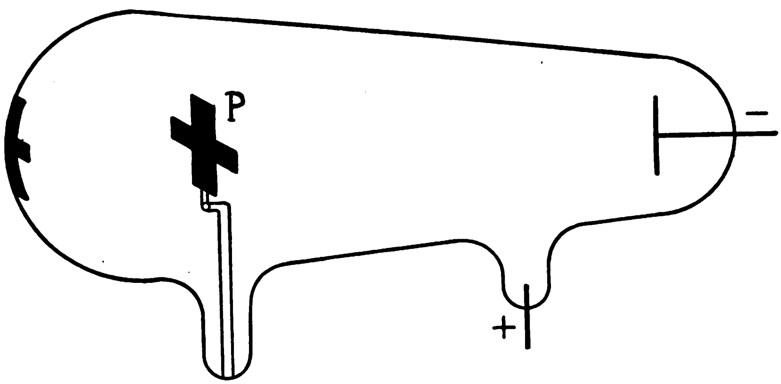

FIG. 46.—Cathode rays cast sharp shadows.

The name *cathode rays* has been given to the faint beam of light. What is their nature? Before answering this question it is desirable to look at some properties of the rays: (1) From what has just been stated, cathode rays are deflected from their path by a magnetic field, and (2) excite fluorescence where they strike the walls of a glass tube. (3) They travel in straight lines. This is readily shown by using a tube of the kind illustrated in Figure 46. With such a tube it is observed that if an obstacle P is placed in the path of the rays, a *sharp* shadow is cast on the end of the tube, all the region around the shadow

strongly fluorescing. This could be caused only by a beam which, ~~like light rays~~, travels in straight lines. (4) Cathode rays represent a considerable amount of kinetic energy. This may be shown by using, not a plane cathode, as represented in Figure 45, but a concave one. By this means the beam of rays (which, it was pointed out above, proceed normally from the cathode) can be brought to a focus at a point, as illustrated in Figure 47. If, now, a thin piece of metal be placed in a tube so that the spot to which the rays are focused is on the surface of the metal, in a short time incandescence will be observed in the neighborhood of the spot. On impact of the rays against the metal a

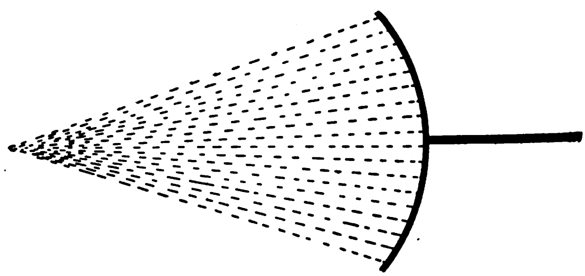

Fig. 47.—Focusing of cathode rays.

large amount of heat is developed. (This point is of very great importance in connection with the action of either the gas or the Coolidge tube.)

(5) Cathode rays are deflected from their path by an *electric* as well as by a magnetic field. To show this a tube constructed as represented in Figure 48 is used. Two pieces of metal A and B with small axial holes are inserted in the tube near the cathode, so that a narrow pencil of cathode rays may be obtained. This beam may be visible for only a short distance from the cathode, if indeed it can be seen at all, but, if at the far end of the tube, a fluorescent screen S be placed, the presence of the rays is at once evident by a round fluorescent spot at O on the screen. Suppose, now, the tube has been constructed with

two metal plates P_1 and P_2 and that these are joined, one to the positive, the other to the negative terminal of a battery. It will then be found that the spot of light shifts from O to K. *In their passage through the electric field between the plates, the rays have been deflected.*

From this and the other properties enumerated, we conclude that cathode rays consist of *a stream of electrified particles.* Moreover, from the direction of the deflection by the electric field, the charge they carry is at once seen to be *negative.*

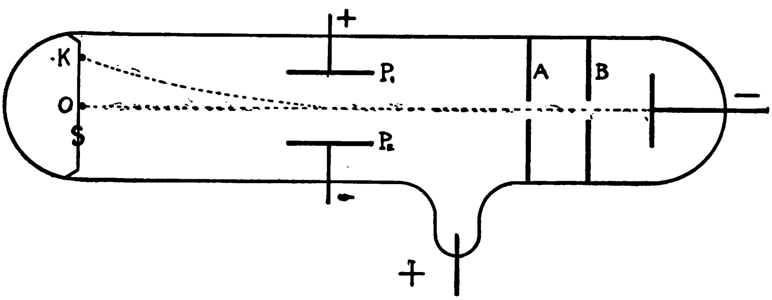

FIG. 48.—Cathode rays are deflected by electric field.

46. How big are these particles? How fast do they move? The answers to these questions are found in quantitative experiments made with tubes of the nature of that shown in Figure 48. Without going into details, it should be evident that the amount of the deflection OK will depend both on the *speed* of the rays and on their *mass,* as well as on the strength of the deflecting electric field. The faster they travel, and the bigger their mass, the less will be the deflection in any given field. By measuring deflections, therefore, for electric (and magnetic) fields of known strength, it is possible to obtain values of the mass and of the speed of cathode rays. Such measurements show that the mass of each particle in a beam of cathode rays is about $\frac{1}{1800}$ of that of a hydrogen atom. The speed

varies with the voltage applied across the tube, but may be of the order of 60,000 miles a second.

Another remarkable fact is evident from such experiments. No matter what gas is used in the vacuum tube, and no matter what the metal used for cathode, the mass of a cathode "ray" is always the same. The general conclusion is obvious: *Cathode rays are just electrons which have been liberated from the atoms of elements and shot down the tube from the region of the cathode. They are high speed electrons.*

Origin of x-Rays

47. When cathode rays strike a metal surface (a target) placed in their path, a new kind of radiation originates at the place of stoppage. These new rays, which possess the remarkable property of being able to penetrate thick layers of apparently opaque substances, are called roentgen or x-rays. The first name is in honor of their discoverer, Roentgen; the second indicates the uncertainty regarding their nature which obtained for some years after their discovery. Later we shall discuss their nature and general properties; at present we are concerned with the mode of obtaining x-rays. This can be done only by having high speed electrified particles (electrons) suddenly stopped. (See however Section 115.)

To obtain a supply of such electrons three different means are utilized. In the first method (the gas x-ray tube), enough gas is left in the exhausted tube so that when a high voltage is applied to the electrodes, a current is conducted across the tube by means of a flow of ions, positive towards the cathode, negative to the anode. Now it has been shown experimentally that between the cathode and a region very close to it there is a big drop in voltage. Accordingly, when the positive ions get near the cathode they are shot (or pulled if you like) at high speed against

it. As a result electrons are liberated either from the gas immediately before the cathode or from the metal of the cathode itself (it cannot be said with absolute certainty which is correct). These liberated electrons in their turn are shot, as a beam of cathode rays, away from the cathode, and when suddenly stopped give rise to x-rays.

In the second and the third methods, as exemplified by the Coolidge and the Lilienfeld tubes, there is not enough gas left in the tube to conduct a current even with extremely high voltages, and electrons are obtained in an entirely different manner. Before beginning a discussion of the new principles underlying the use of these tubes, however, it is desirable to examine in detail the construction and the operation of the gas bulb.

CHAPTER V

THE GAS BULB

48. The main features of the type of gas tube in most common use for either coil or transformer are illustrated in Figure 49. C is the cathode, with face concave or cup-shaped, so that, as noted in Section 45, the cathode rays are brought to a focus on the face of the target. From the focus spot x-rays spread out in all directions, passing through the whole half of the hemisphere in front of the

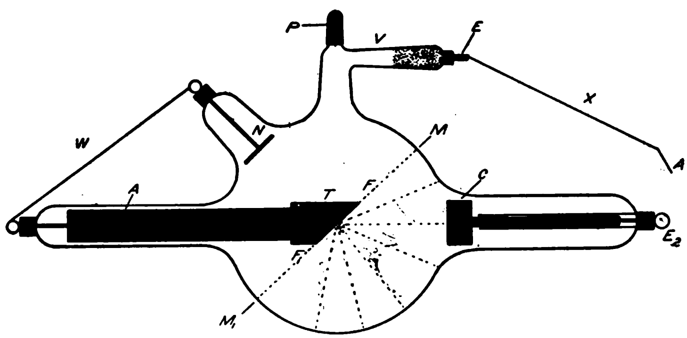

FIG. 49.—Typical gas x-ray tube.

plane MFM′. Here it may be noted that when the current through a gas tube is in the right direction, the portion of the bulb in front of the plane MFM′ is usually strongly fluorescent, being separated from the remainder by a sharp line of demarcation. The target T forms the end of a long metal arm A, the anticathode, which by means of the connecting wire W, is in electrical contact with N the anode. The anode N lies within a short side arm of the tube, and does not project into the main body of the

RUNAGOUT

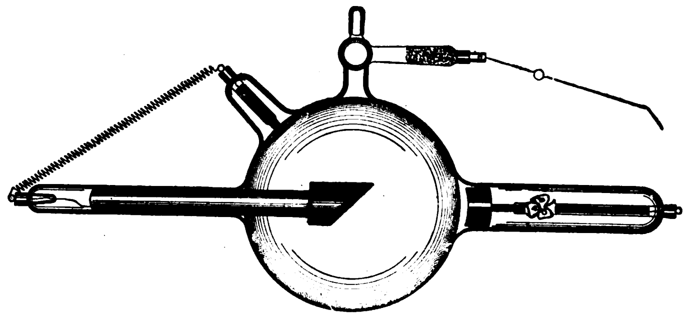

FIG. 50.—Gas tube (Waite and Bartlett Co.).

tube. V is another side tube which carries a third electrode E, and is added for the purpose of regulating the gas pressure in the bulb. P represents a rubber tip covering the place at which the tube was sealed off from the exhaust pump after the initial exhaustion had been completed.

REGULATION OF THE VACUUM

49. It will be seen later that the nature of the beam of x-rays leaving a tube depends both on the current, that is, the milliamperage (ma.) and on the voltage across its terminals (the back-up). An operator, therefore, must be able to control both the current and the voltage. Now, if the vacuum remains constant, the higher the voltage applied to a tube, the greater the current through it. (See Section 52.) There are cases, however, where an operator may wish to change to a *higher* voltage without altering the milliamperage, or possibly with even a *smaller* milliamperage. How can this be done? To understand the answer to that question it is necessary to remember that the voltage required to maintain a given current through an ordinary vacuum tube varies with the pressure of the contained gas. If, therefore, by any means the gas pressure in any x-ray bulb is altered a different voltage will be required to pass the same current through it. If the

vacuum is lowered (pressure increased), the resistance of the tube decreases or it becomes "softer." If the vacuum is raised, the tube runs "harder," that is, the resistance increases. A soft tube, therefore, is more conducting than a hard one.* Putting it in another way, a higher voltage or a bigger back-up is necessary to maintain a certain milliamperage through a tube when it is hard than when it is soft.

The desired regulation of voltage and current may be obtained, (1) by having a series of tubes, for example, one soft, one medium, one hard; (2) by altering the pressure of the gas in a single tube. The first method is to be preferred for tubes which will maintain a fairly constant vacuum. (See Section 53.) Since, however, vacuum changes in a tube are ultimately inevitable, method (2) must be used to some extent, even in the case of an outfit which includes a number of tubes.

50. But, it is asked, how can one vary the pressure in a tube which is sealed and cut off from any connection with an exhaust pump? Such a variation is possible because all gas tubes are supplied with what are called *vacuum regulators*. Reference will be made to three of these. (1) In the kind in most general use, a side arm, V, (Figure 49) provided with an electrode E, and containing some substance such as asbestos wool, charcoal, lime, etc., is sealed on to the tube. Such substances contain a certain amount of "adsorbed" gas, some of which is released when the substance is warmed. The usual method of warming the regulator consists in passing an electric discharge between the electrode E and one of the main terminals of the tube. For this reason, whenever a gas tube is used at any appreciable distance from a transformer or coil, three lead wires are invariably used. A glance at Figure 51 will show the reason for this. In this figure C

* Later we shall see that the terms hard and soft are also used to describe the character of the rays leaving a tube.

and D represent the high tension terminals, while AC is a metal rod capable of being rotated about C, but normally in the position shown in the figure. When the x-ray switch is closed, the current passes through the tube circuit and the tube in the usual way. Suppose, however, that by means of a cord R attached to the rod AC, it is pulled aside to the dotted position until the end A touches B, a "binding post" on an insulated support. If, now, B is attached by means of a flexible conducting cord to E,

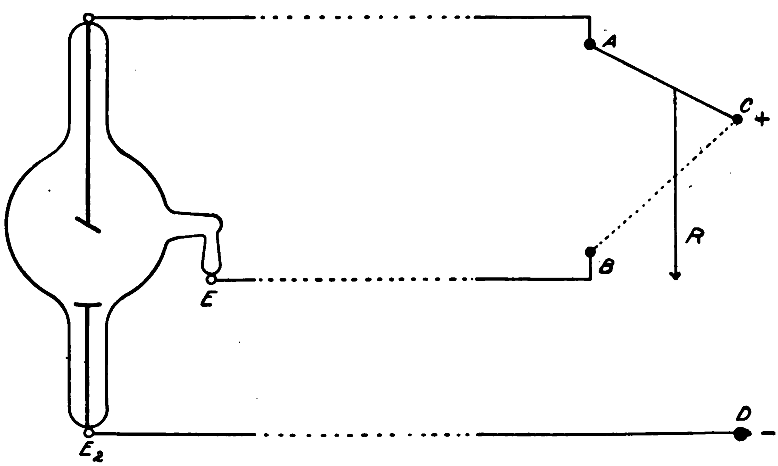

FIG. 51.—Use of vacuum regulator and third wire.

the electrode of the vacuum regulator, it is evident that, on closing the x-ray switch with the rod in this position, the discharge passes through the tube from the vacuum electrode to the terminal E_2. As a result of such a discharge the substance in the regulator is heated and a certain amount of gas (largely carbon dioxide and water vapor) liberated. As a rule, only a small quantity of gas is required and care must be exercised not to allow such a discharge to pass for any but the shortest intervals of time. If such a precaution is not taken the pressure may be raised too much and re-exhaustion of the tube may be necessary.

Occasionally the regulator is used in such a way that, if the tube becomes too hard when in operation, it is automatically softened. To accomplish this the third wire is dispensed with and use is made of an adjustable flexible wire X (Figure 49), permanently attached to the electrode E. Suppose this wire is set with its end A near one of the tube terminals, but at such a distance that no spark jumps across. It will be seen that (provided the distance A to E_2 is not too great), if the tube should harden appreciably when in operation, the higher voltage across the tube will cause a spark to jump this gap, thus sending a discharge through the regulator. Gas will then be liberated, the tube will be softened, the voltage across the tube will drop and sparking A to E_2 will cease.

The vacuum regulator we have been discussing is of use only in *lowering* the vacuum. Suppose the pressure in a tube is too high, how can it be *reduced* (that is, the vacuum *raised*)? This can be done to some extent in at least three different ways, (1) by operating the tube with small currents until it is quite hot, (2) by setting the tube aside for some length of time, (3) by cooling the vacuum regulator.* As noted in Section 54 below, a tube hardens when in use because of the adsorption of gas by the glass walls, the metal electrodes and possibly the regulating substance itself. The hardening because of method (2) simply means that this adsorbing process increases with time. In the case of regulators containing some hygroscopic substance such as asbestos packing, method (3) has been used with success by Levy and Mann.[1] These workers have shown that with such regulators tubes may be conveniently hardened by cooling the regulator by means of an ethyl chloride spray. For exact details of using this method, which is extremely simple, the reader is referred to the original article. The

* The writer is acquainted with one operator who hardens his tubes by running a reverse current through the tube. This method, however, is not the best for the tube.

method is based on two sound scientific principles. (a) Water vapor in an enclosed vessel will condense until it has the equilibrium pressure corresponding to the lowest temperature of any part of the vessel. In this case the regulator tube becomes coated with snow and ice. (b) The adsorption of gas, at least in the case of many substances, increases with decreasing temperature. Research workers when using apparatus in which a high vacuum is necessary, frequently attain the required low pressure by attaching to their apparatus a tube containing cocoanut charcoal immersed in liquid air. At the low temperature of liquid air the adsorption of the charcoal is very great.

It is desirable, however, to have a tube too hard rather than too soft, for, as noted above, the remedy for too great softness is re-exhaustion.

In this connection attention may be called to an article by Mutscheller,[2] in which he describes a gas tube with a somewhat new type of regulator. To begin with, use is made of a new substance which consists of a mixture of nitrides of metals such as thorium, aluminium, barium, etc., and, it is claimed, has the property not only of liberating nitrogen when warmed by a discharge in the usual way, but also of absorbing or "adsorbing" nitrogen from its surroundings. With such a substance, therefore, because of this adsorption, the tube on standing automatically returns to the hard state. On each occasion when it is desired to use the tube it must be softened to the desired degree. To guard against over-softening a device is added, as a result of which, once a certain pressure has been attained in the bulb, the discharge instead of passing from the electrode through the substance, passes from the electrode to a metal cylinder surrounding the substance and then through the main part of the tube. For details, the reader is referred to the original article. In this tube, an illustration of which is given in Figure 52, it is well to note that the residual gas is nitrogen.

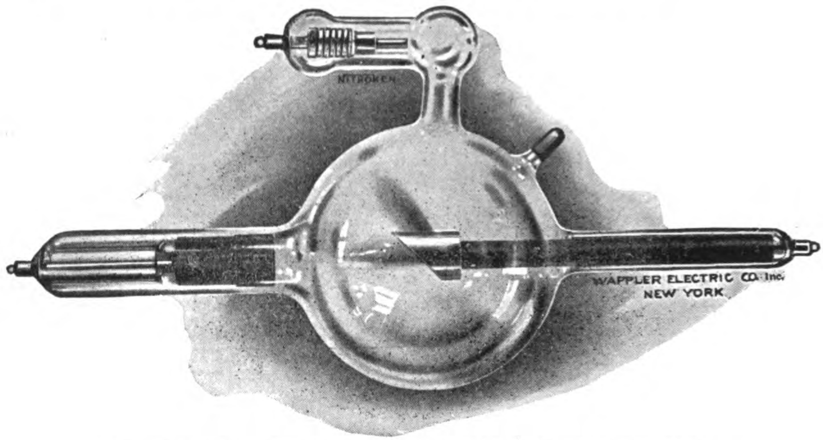

FIG. 52.—The Nitrogen gas tube (Wappler Electric Co.).

THE PALLADIUM TUBE

(2) The metals palladium and, to some extent, platinum are porous to the gas hydrogen. Use is made of this property to regulate the vacuum in a gas tube. The device is extremely simple. Instead of the regulator just described the bulb has a side tube somewhat as illustrated in Figure

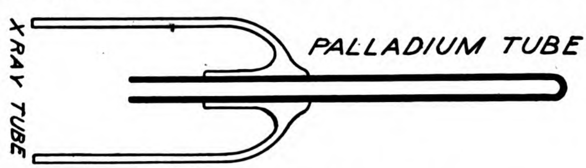

FIG. 53.—Palladium tube, to regulate vacuum.

53. Through one end of this is sealed a palladium tube, with the end inside the bulb open, the end outside closed. To soften a tube with such a device all that is necessary is to place a small flame of burning hydrogen (illuminating gas will do) in contact with the closed end of the palladium tube. Hydrogen will then diffuse inside the bulb. If illuminating gas is used, in order to ensure an excess of hydrogen, no air should be supplied the flame.

A palladium tube may also be used to harden a tube provided it contains hydrogen as the residual gas. To use it for this purpose the external portion of the tube must be warmed in an atmosphere *free from hydrogen.* In this connection reference may be made to the so-called Hydrex tube, which is provided with two palladium tubes, one (A) enclosed in a small bulb containing hydrogen at a pressure considerably greater than that within the x-ray tube itself; the other (B) open to the air. If A is heated, hydrogen passes into the bulb; if B is heated, hydrogen passes out.

The Bauer Valve

(3) This is a third device for softening a tube. By means of it small quantities of air from the surrounding atmosphere may be admitted to the tube. The principle will be understood by reference to Figure 54 (taken from Kaye's *X-Rays*). Connection between an unglazed porcelain tube and the outside air can only be established when the column of mercury, indicated by the black line, moves past P, the junction of the porcelain tube with the mercury column. Normally the air pressure in the chamber C is such that this connection is sealed. If, however, by means of a pneumatic pump (the bulb of a syringe might do), the mercury is forced past the junction, air from the outside can enter the porcelain tube, and hence diffuse through its pores into the tube. To prevent the passage of mercury vapor into the x-ray bulb, the porcelain tube contains a pack-

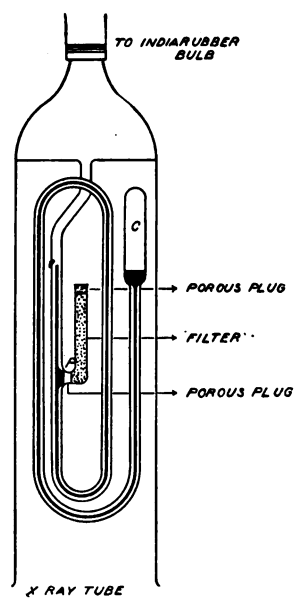

FIG. 54.—Bauer valve, to regulate vacuum.

ing of gold leaf. As the mercury quickly returns to its normal position, only small quantities of air are admitted at a time.

Rating the Vacuum

51. It will be evident that the terms hard and soft are very general ones. There must be a border line condition, for which one might describe a tube as "not very hard" or "not very soft." It is natural to ask, therefore, if there is not a more exact way of describing the resistance of a tube. It will be recalled that when one is dealing with conductors such as ordinary wires, filament lamps, etc., their resistance is expressed as so many ohms. With such conductors it is found by experiment that, if we take any given resistance, the current through it is always proportional to the voltage across its ends; that is to say, if we double the voltage, the current is doubled; triple the voltage, the current is tripled, and so on. As a consequence of this experimental law (Ohm's Law), the number obtained by taking the ratio $\frac{\text{volts}}{\text{amperes}}$ is taken as a measure of the resistance of the conductor. For example, if, when 12 volts are applied to a conductor the current is 2 amperes, the resistance is $\frac{12}{2}$ or 6 ohms. [If 6 volts had been applied, the current would have been 1 ampere.]

52. Is there any corresponding way of expressing the resistance (degree of hardness) of an x-ray tube? To answer that question, we must resort to experiment. Suppose, with tube vacuum as constant as possible, we vary the voltage across the tube and for each value note the corresponding current (ma.) through it. Do we find any simple relation between volts and milliamperes? According to the data given in Tables III and IV (a record of some results published by the Wappler Electric Company, and reproduced with their kind permission) there is an approximate

TABLE IV, TUBE A

Voltage (Inches gap)	*Current* (in ma.)	$\frac{(\textit{Inches})^2}{\text{gap}}$
6″	40	.90
5″	29	.86
4½″	23	.88
4″	17	.94
3″	10	.90

TABLE V, TUBE B

Voltage (Inches gap)	*Current* (in ma.)	$\frac{(\textit{Inches})^2}{\text{gap}}$
5″	40	.62
4″	27	.59
3½″	21	.58
3″	14	.64

law. In Table IV, for example, it will be noted that the ratio $\frac{(\text{voltage})^2}{\text{ma.}}$ is approximately equal to 0.9 for all values of the current. This means that if the voltage be doubled, the current becomes four times as great; if trebled, the current will be nine times as great. In Table V similar readings for a softer tube are given. In this case, the ratio $\frac{(\text{voltage})^2}{\text{ma.}} = 0.6$ approximately, and the same law holds roughly—double the voltage, the milliamperage is fourfold.

The law, however, is not exact, although the figures do establish its approximate truth. Moreover, they show why it is possible to express the degree of hardness of a gas tube by a number, as has been done by the Wappler Electric Company. Tube A (Table IV), for example, is said to have a 0.9 vacuum. Tube B (Table V) a .62 vacuum. To illustrate once more, in this system a tube with a 0.4 vacuum, is one through which a current of 40 ma. is passed when the back-up is 4″ $\left[\frac{4^2}{40} = .4\right]$. Such a tube is of medium hardness and suitable for all average work. If a tube is hardened so that a back-up of 6″ is required to pass 40 ma., the vacuum is now 0.9, that is, $\frac{6^2}{40}$. As a matter of practice, however, there is not much need for rating the vacuum. An operator soon knows by experience what voltage and milliamperage is required for the particular case in hand, and will choose his tube accordingly

or will regulate the vacuum until the proper combination has been obtained.

Constancy of the Vacuum

53. In radiography it is desirable and in treatment it is highly important that an x-ray bulb should maintain a given vacuum for some length of time. With a tube which has been properly handled, this is the case. When first used, gas is liable to be liberated from the electrodes of a new tube, and the vacuum alters. If, however, care is exercised to avoid initially the use of long exposures and heavy currents, the tube ultimately settles into what is called a "seasoned" condition. "Once a tube is seasoned it will maintain its vacuum and degree of hardness for long periods and may be used for hours daily." (Knox.) For that reason it is desirable to have a range of tubes of varying degrees of hardness and to avoid as much as possible the use of the vacuum regulator. But the possession of a range of tubes, all maintaining a constant vacuum, is more or less an ideal state of affairs and vacuum regulators are indispensable. Here again we may refer to the tube with the regulator described by Mutscheller, which, it is claimed, makes it possible to adjust a tube to conditions ranging from very soft to very hard. Moreover, once this tube has been set in a given state, a constant vacuum is maintained for all ordinary time intervals required in radiography.

In using x-rays for treatment, the tube current should remain constant for long intervals of time. This is not an easy matter to attain with a gas tube but it is not impossible. In one device the writer has seen a relay is connected with the secondary (tube) circuit in such a way that, when the current falls before the desired constant value, there is an automatic release of a puff of gas from a jet. A spark ignites the gas, the resulting flame playing on an

osmosis (palladium) tube. Hydrogen, therefore, passes into the tube, the vacuum is lowered and the tube current increases. As soon as its magnitude has reached the desired constant value, the gas is automatically cut off. With such a device, therefore, the gas jet is intermittently on and off and the tube current maintained constant, within narrow limits.

Action of the Tube

54. A vacuum regulator is necessary for another and a very important reason. In the case of a tube which has been in use for some time two things are observed: (1) the tube gradually runs harder; (2) the glass walls of the tube are gradually coated with a black metallic deposit which looks much the same as the black coating often seen on an old tungsten filament incandescent lamp. Now this gradual hardening is due largely, if not altogether, to the absorption or adsorption of the residual gas by the walls and electrodes of the tube. After a time, therefore, it is absolutely necessary to use some means of letting a little gas in a tube.

The adsorption is increased by the presence of the metallic coating, and herein lies one reason why such blackening is undesirable and should be avoided as much as possible. Three other objections to the presence of blackening may be stated: (1) it increases the resistance of the tube; (2) sparking along the walls rather than through the gas is liable to take place; (3) the danger of puncture is increased. "Experiments in the laboratory have shown that a grounded metal wire can be brought up into contact with a clear bulb when the tube is operating, whereas with a tube having a metal deposit inside, such a wire must be moved away a number of inches to avoid puncturing the tube." (C. N. Moore, General Electric Company.)

Causes of the Blackening of a Gas Tube

55. We can understand how best to minimize blackening by noting that it is the result of two causes: (1) the evaporation and disintegration of hot metals; (2) a cathodic disintegration known as "sputtering." Sputtering consists of the ejection of metallic particles from the cathode. These particles are small pieces of metal and must not be confused with electrons.

In a good tube, therefore, blackening is minimized, (1) by choosing as metal for the cathode one which sputters a minimum amount; (2) by keeping the tube and especially the metal parts as cool as possible, and so preventing vaporization. Moreover, as the greater the current which is used the more marked is each of these phenomena, obviously heavy currents should not be used any more than is necessary. In the actual construction of the bulb, however, means are taken to minimize the causes of blackening. These can best be explained by referring briefly to further details in connection with the construction of the tube.

The Cathode

56. To obtain x-rays for good radiographs, as already noted, cathode rays must be focused at a small region on the face of the target. The focusing is done partly by the curved shape of the cathode, partly also because the walls of the glass and the layers of air adjacent to the electrode become negatively charged and exert a repulsive force on the negative rays. This force repels the cathode rays to the center of the target, so that even with a plane cathode a certain amount of focusing takes place. To some extent also the nature of the focusing depends on the gas pressure. Here it may be noted that it is not desirable to have the high tension transformer too near the tube because the effect of the strong magnetic field on the cathode beam may be injurious to proper focusing.

The choice of the metal used for the cathode depends largely on the degree to which sputtering exists. Experiment has shown that tungsten, tantalum, and aluminium in comparison with metals such as platinum, silver, and lead sputter remarkably little. Aluminium, therefore, which is so readily obtained, is invariably used as the cathode. (To prevent sputtering from the wires connecting the cathode with the external electrode, these wires are sometimes encased in glass tubing.)

The Anticathode

57. We have seen in the preceding chapter that a beam of cathode rays represents a considerable amount of energy. At the focal spot, where this energy is concentrated, enough heat may be developed to melt and so puncture the target. But, even if the face of the target is not punctured, the metal may be heated to such a degree that it easily vaporizes, and subsequently is deposited on the walls of the tube. Evidently it is desirable (1) to choose a metal for the target which has a high melting point; (2) to keep the target as cool as possible.

In Table VI will be found numerical data relating to certain metals which are of interest to the x-ray worker.

Table VI

Metal	*Atomic Weight*	*Atomic Number*	*Melting Point*	*Thermal Conductivity*	*Specific Heat*	*Volatilization Detectable at*
Platinum	195.2	78	1750° C.	0.17	.03	1200° C.
Iridium	193.1	77	2290° C.	0.17	.03	1400° C.
Osmium	190.9	76	2700° C.	0.17	.03	2300° C.
Tungsten	184	74	3300° C.	0.35	.03	1800° C.
Tantalum	181.5	73	2900° C.	0.12	.04	......
Molybdenum ..	96	42	2500° C.	...	.07	....
Copper	63.6	29	1084° C.	0.92	.09	....
Nickel	58.7	28	1450° C.	0.14	.10	....

It will be seen that platinum, which for several years was the metal used to the greatest extent as anticathode, is by no means the most satisfactory. Compare it with tungsten, for example. Its melting point, 1750° C., is little more than half that of tungsten, 3300° C. Moreover, platinum is one of the metals which sputters readily, whereas tungsten sputters but little. For this reason, should any inverse be present in the case of a platinum target tube, blackening would soon be pronounced. (During inverse

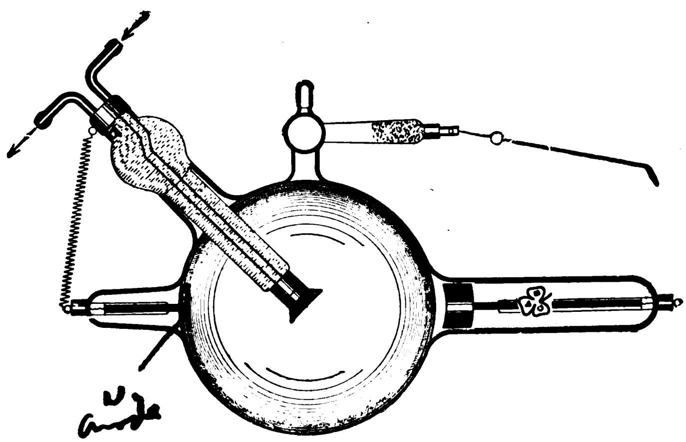

Fig. 55.—Tube with water-cooled target (Wappler Electric Co.).

the anticathode will act as cathode.) In recent years, therefore, tungsten has been gradually replacing platinum, partly, perhaps largely, because of the research work of the General Electric Company, Schenectady, on the production of wrought tungsten.

The choice of a metal with high melting point is not in itself sufficient to prevent vaporization. If no means are taken to conduct heat away from the focal spot the temperature will steadily rise and some volatilization will soon take place. A glance at the figures in the last column of Table VI will show that evaporation of a metal may take place at temperatures considerably below the melting point.

In a good anticathode, therefore, some means is used to prevent the temperature from rising quickly. This is done to some extent by using a heavy piece of metal as connecting link between the target and the external electrode of the anticathode. Copper, because of its high thermal conductivity, as well as its high specific heat, is a suitable metal. Additional cooling is sometimes provided by attaching to the end of the anticathode outside the tube, thin sheets of metal which act as radiators of heat. (A good example of this is found in the radiator type of Coolidge tube, to be discussed in the next chapter. See Figure 72.)

Another means is found in the use of water cooled targets. In this case (see Figure 55) the hollow anticathode is filled with water, which, accordingly, is directly in contact with the back of the target. Because of convection currents set up in the water, or because of an actual flow of water, the temperature of the target may be kept at or below 100° C., and practically all the evil effects of hot targets eliminated.

Output of X-Rays

58. Another important reason for using metals of high melting point is found in the fact that such metals are usually also of high atomic weight. Now, other conditions being the same, the intensity of a beam of x-rays emitted by a tube increases with the atomic weight, or, putting it in another way, is proportional to the atomic number (see Section 42). In this respect there is not much to choose between platinum, iridium, osmium, tungsten and tantalum, but any of these is markedly superior to nickel, for example.

Regarding this whole question of output we may note one or two further points. If we look on an x-ray tube as a "machine" for the generation of what we call x-rays, it is remarkably inefficient. Only an extremely small fraction of the total electric energy supplied a tube is changed into the energy represented by the x-rays themselves. The

intensity of the beam, however, depends on the energy supplied the tube per second, or, as noted in Section 21, on the product volts × milliamperes. (See Sections 108, 123.) By steadily increasing this product the intensity of the x-ray beam steadily increases. There is, however, a limit to the energy (volts × milliamperes × time) which may be supplied a tube. This limit depends largely on the rate at which the temperature of the cathode rises. With a "fine focus" tube, for example, that is, in the case of one in which the cathode beam is focused to a small area, less energy can be supplied than with a broader focus tube. In the latter case the intense heat generated at the focal spot is spread over a larger area. Again the larger the tube, in general the greater the amount of energy which may with safety be supplied it.

To sum up, every tube has a maximum allowable input of energy and an operator should always be extremely careful not to exceed this maximum. It would be a wise precaution if on every tube this value were plainly marked. This would at least help to prevent the ruining of a tube which sometimes occurs at the very outset of its career.

The Auxiliary Anode

59. In almost all gas tubes the anticathode is in electrical connection with an auxiliary anode (N, Figure 49). Such an additional electrode is not necessary and, to quote from Kaye's admirable book on x-rays, its "precise benefit is doubtful." Two or three points in connection with it, however, may be noted. A discharge passes with difficulty through a vacuum tube when the anode is within the dark space. (See Section 44.) Now, in the case of an x-ray tube, as we have already seen, exhaustion is continued until the dark space fills the whole body of the tube. If, therefore, no auxiliary anode were present, since the target is in the center of the tube, the discharge would pass with

greater difficulty. Again we have seen that the old type of valve tube (see Section 38) acts as a rectifier, because the less restricted electrode in a tube functions more readily as cathode. Accordingly, without the auxiliary anode, the anticathode (being less restricted) would tend to act as cathode and actually help to suppress current in the right direction. Finally should inverse current be present, there is an advantage in having an auxiliary anode made of aluminium which, as already noted, sputters an exceptionally small amount.

Danger of Inverse

60. In section 48 it was pointed out that, when the tube current is in the right direction, the whole half of the bulb in front of the plane MFM′ (Figure 49) is fluorescent and separated from the other half by a sharp line of demarcation. When the current is in the wrong direction there is no sharp line and the central portion of the tube is not divided into two well-defined halves. In this case the glass in the region of the cathode exhibits fluorescence in a somewhat irregular fashion that may vary with the particular tube used. This fluorescence is the result of the impact on the walls of the tube of cathode rays sent from the target (the cathode during inverse) and may be looked on as a danger signal. It means that there will be an excess of heat developed at the regions where the fluorescence exists, with consequent possibility of a tube puncture. The x-ray switch should at once be opened or the loss of a tube may be the penalty.

The Residual Gas

61. In section 50 reference has been made to a tube in which, because the residual gas is hydrogen, it is possible either to raise or to lower the vacuum by means of palladium tubes. Obviously in this tube the residual gas must

be hydrogen. In the same section, however, it was stated that the gases liberated from the ordinary vacuum regulators are carbon dioxide and water vapor. Which gas, therefore, if any, is the most suitable? Is there any decided advantage in one over all the others? Consider, first, the question of constancy of vacuum. We have seen that, because of the adsorption of the residual gas by the walls of the tube, as well as by metal surfaces inside it, there is always a progressive hardening. Is this phenomenon more marked with some gases than others? A partial answer to that question is found in the research work of the General Electric Company, of Schenectady, and in that of Mutscheller, of the Wappler Electric Company. The former work has shown that all gases are adsorbed by the glass walls of a tube, while oxygen and nitrogen combine with hot tungsten. The experiments of Mutscheller have shown that with the metals copper, iron and aluminium there is less absorption of nitrogen than of oxygen and hydrogen. He concludes, therefore, that nitrogen is the most suitable residual gas, and because of such experiments has designed the nitrogen tube with the vacuum regulator already described. In this tube, it will be recalled, the gas released by the regulating substances is nitrogen.

Again, according to Kaye, bulbs originally filled with hydrogen, nitrogen, and carbon dioxide show less sputtering than is the case with air and presumably oxygen. Moreover, volatilization is much less marked in the case of platinum, rhodium and iridium when oxygen is absent from the surrounding gas. For these reasons, therefore, it does not seem desirable to use air as the residual gas because of the large percentage of oxygen present. On the other hand, to quote Kaye once more, "for the same pressure a tube runs harder in hydrogen and still harder in carbon dioxide than in air" and "a tube rendered unsteady by the hardening effect of hydrogen may often be caused to run smoothly by letting in a little air."

To sum up, there does not seem to be overwhelming evidence in favor of the marked superiority of one gas over another, although something is to be said for nitrogen. Possibly the extent to which the Coolidge tube is replacing the gas tube is at least partly responsible for the lack of conclusive evidence on this point.

The High Frequency Tube

62. This is a gas tube designed to operate on a high frequency outfit. Without going into details we may note that with such apparatus an *alternating* high voltage (with high frequency) is available. The ordinary tube is, there-

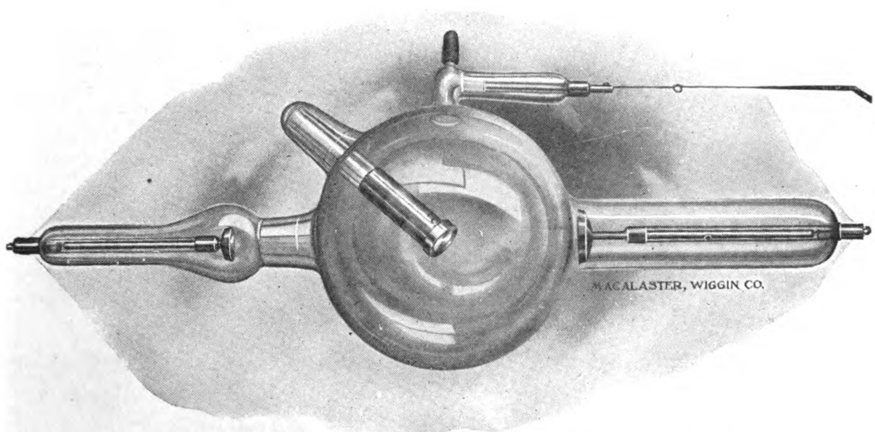

Fig. 56.—High frequency tube (Wappler Electric Co.).

fore, not suitable for use in such a case. In almost any catalogue, however, one may find a tube illustrated of the type shown in Figure 56 and Figure 57. This tube differs in two respects from the ordinary gas bulb: (1) the anti-cathode (A) has no external connection; (2) the end (C) of the electrode which functions as the anode is behind a constriction (*d*). Now the question to be explained is this.

When an alternating high voltage is applied directly to the terminals E_1 and E_2, why does current pass only when E_1 is the cathode? The reason is given in the words of Mr. C. N. Moore, of the Research Laboratory, General Electric Company. "During the half-wave when *a* is negative, the cathode stream from *a* impinges upon *b* producing x-rays, and the charge leaks off through the gas to *c*. When *c* is negative, there is no cathode stream from *c* because the constriction at *d* prevents bombardment of it by positive ions and the escape of electrons from the small side bulb. Thus no current passes through the tube during this

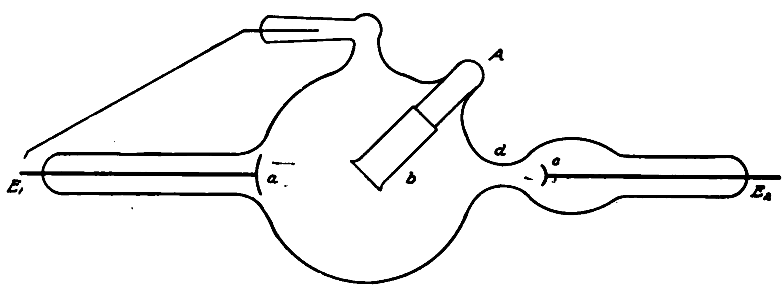

FIG. 57.—High frequency tube.

half-wave." In other words, this type of tube is its own rectifier.

62A. In conclusion, it should be evident that, in buying a gas tube, the exact kind of apparatus with which it is to be used should always be stated. A high frequency tube, for example, is not meant for use with a transformer outfit. Moreover, even a tube most suitably chosen is liable to exhibit certain idiosyncrasies. The intelligent operation of any kind of tube is possible only by one who understands something of the nature of the passage of electricity through a gas. In the last two chapters of this course, the writer has tried to present the necessary fundamental principles of this branch of electricity. It would not be fitting if he concluded them without expressing his indebtedness to the

authoritative book to which reference has already been made more than once, Major G. W. Kaye's *X-rays*.

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2. Mutscheller, *Amer. Jour. of Roent.*, VII, 5, 261, 1920.

CHAPTER VI

THE COOLIDGE TUBE

Thermionic Emission of Electrons

63. It has already been noted that in a Coolidge tube the vacuum is nearly as perfect as modern means of exhaustion can make it. So high is the vacuum that if an attempt is made to use it as a gas tube, no current passes even with 150,000 volts across the tube. How, then, does it operate? To answer that question, it is necessary first of all to explain what is meant by a thermionic emission of electrons. This can best be done with reference to one or two simple experiments. In Figure 58 B′ represents a highly exhausted glass bulb provided with three electrodes, 3 joined to an inner sheet of metal P; 1 and 2 to the ends of a filament F of fine wire, tungsten for example. Suppose, now, that 1 and 2 are connected to a storage battery by means of which current may flow through the filament and heat it to incandescence. Suppose, further, that a second circuit is made by joining 110 D.C. terminals (A and B) as illustrated in the figure, where G represents a galvanometer or any sensitive current-measuring instrument. A deflection of G will then indicate a current flowing around the circuit A to G to 3 to plate to filament to 1 to B. Is there any such current? We may distinguish two cases. (1) With filament cold, that is, key open, it is found that, no matter what the polarity of A and B is, no current is indicated by G. (2) With the filament incandescent (key closed), however, if B is negative, a marked current is indicated, whereas if B is positive, no current passes. Evidently,

therefore, a current passes through such a tube when the filament is hot and when it is negative. Now, what is the explanation? It is found in the fact that any hot piece of metal is a source of electrons. At the surface of metals a process somewhat akin to evaporation goes on, as a result of which, at high temperatures, there is a copious emission of electrons known as a *thermionic emission.*

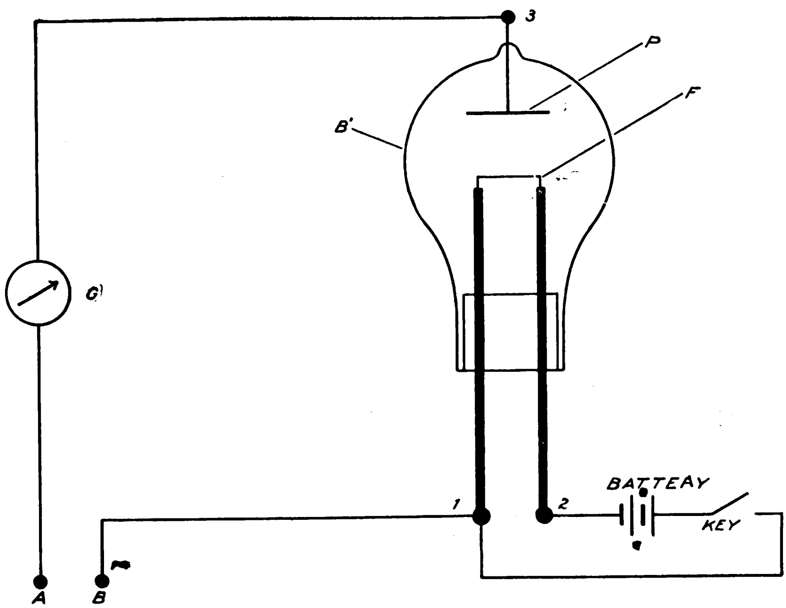

FIG. 58.—Connections for experiment to illustrate thermionic emission of electrons.

In the above tube, therefore, the hot filament liberates electrons; if the filament is negative, and the plate positive, since negative repels and positive attracts negative electricity, these electrons are driven across the vacuum space. There is, therefore, a current of electricity which, in this case, consists of a stream of negatively charged electrons. If the filament is positive, however, because of the attraction of positive for negative, the electrons cannot escape from the filament and no such current exists.

Hot Filament Rectifiers—the Kenotron

64. It should now be evident that if 110 volts *alternating* is applied to AB a stream of electrons will cross the tube only during the half cycle when the filament is negative. In other words, an intermittent but uni-directional current flows in the circuit containing G, although an alternating voltage is applied. Such a three-electrode tube, therefore, is an excellent rectifier and has many practical applications. The use of such a valve tube in "Radio" will be familiar to many readers, while we have already made reference (Section 38) to such a means of suppressing inverse current. The same principle is utilized in the *Kenotron,* a device perfected by Dr. S. Dushmann of the General Electric Research Laboratory, for the rectification of a high tension voltage.

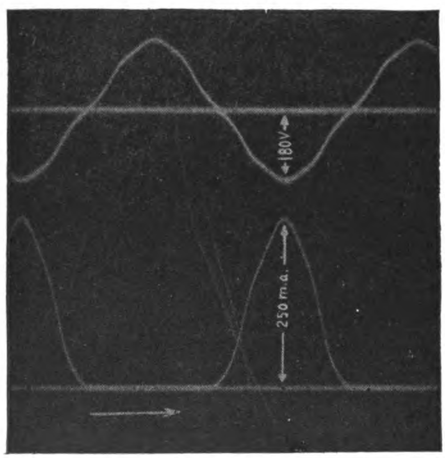

Fig. 59.—Oscillogram showing rectification (lower graph) of alternating current (upper graph), by use of kenotron (General Electric Co.).

How perfect is the rectification is well shown in Figure 59, where the upper curve shows the variation in the alternating voltage applied to a kenotron, while the perfect uni-directional, although intermittent, current is clearly shown in the lower curve.

65. Now the Coolidge x-ray tube, for which we have to thank the genius of Dr. W. D. Coolidge, is a direct application of the principle of thermionic emission. It differs from the gas tube not because x-rays originate for any different reason but because the stream of high speed elec-

trons has its origin in an incandescent filament of metal. To heat the filament, an independent circuit, called the

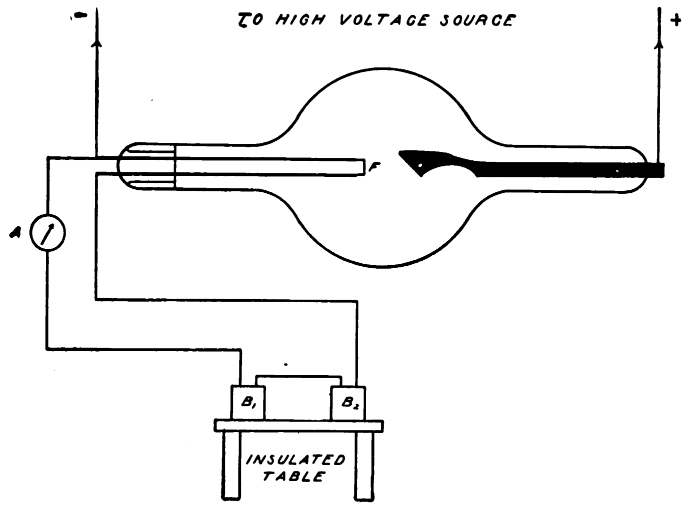

FIG. 60.—Connections for filament circuit, with storage battery.

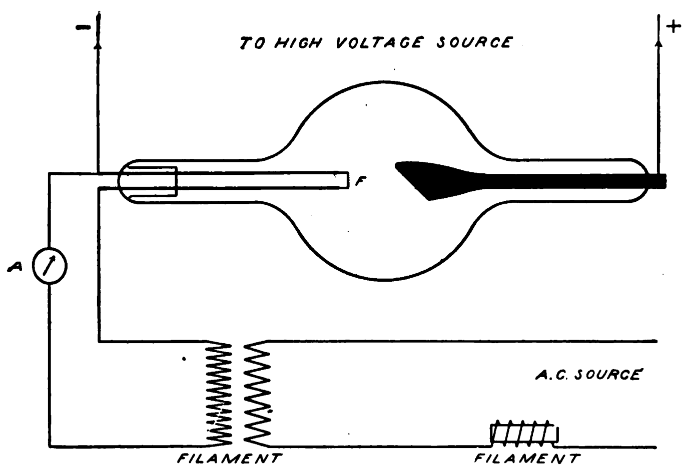

FIG. 61.—Connections for filament circuit, with filament transformer.

filament circuit, is necessary. In the original arrangement (Figure 60), a storage battery B_1 and B_2 was used as the

source of supply for this circuit. In the arrangement now on the market (Figure 61), a branch from the A.C. mains supplies a small filament transformer, the secondary of which is connected in series with the filament. While this arrangement is more convenient it has one disadvantage. Voltage fluctuations on the line will cause corresponding

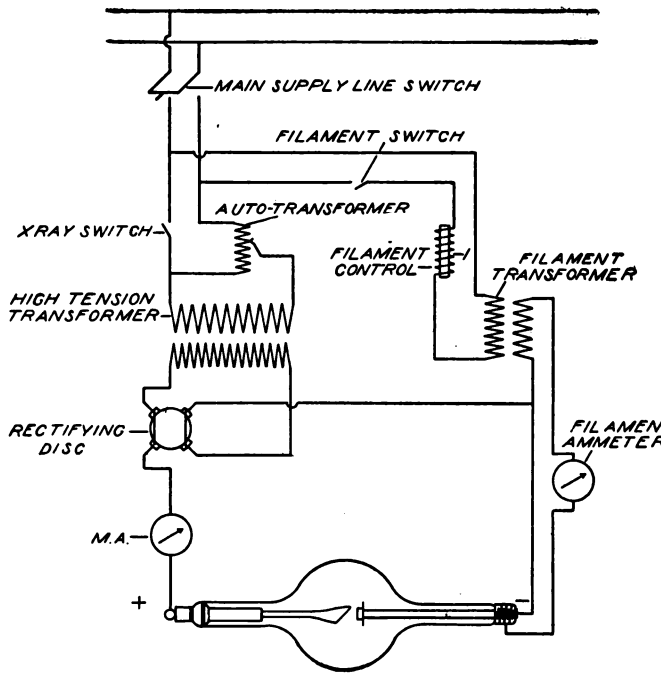

FIG. 62.—Complete connections for a Coolidge tube, with filament transformer, and auto-transformer control of high tension voltage.

fluctuations in the filament and consequently, as we shall see later, alter the milliamperage through the tube.

To give the necessary high speed to the liberated electrons the high tension voltage is applied to the tube in the usual way, the hot filament being, of course, negative. Since the whole filament circuit is raised to the high potential of the cathode, it is necessary to insulate the storage battery (or the filament transformer). The complete cir-

cuit for the ordinary Coolidge tube, therefore, includes (1) the usual high tension circuit, (2) the filament circuit. In Figure 62 connections for the complete arrangement (minus the synchronous motor circuit) are shown. It will be seen that the high tension circuit, which in this case has the auto-transformer control, is exactly the same as that already discussed. The new feature is the filament circuit controlled by the filament switch and containing an ammeter to enable an operator to read the current heating the filament. By means of the filament control I (a variable inductance) the strength of the current may be altered. Before discussing details of control, however, it is desirable next to look at some further points in connection with the tube itself. There are some half dozen types of tube now on the market, but in the meantime our remarks shall refer primarily to the standard so-called "Universal" type.

The Universal Standard Tube

66. To obtain the necessary high degree of exhaustion, and to eliminate as much as possible all traces of residual gas, elaborate precautions are taken. "All metal parts before being mounted are fired in a quartz tube vacuum furnace at 900° C. for about an hour, and are allowed to cool down in a vacuum so as to prevent oxidation. The purpose of this firing is to render the parts perfectly clean and to remove partially the occluded gases."[1] During exhaustion the tube itself is heated in an oven at about 400° C. for three-quarters of an hour. After this process the tube is operated at higher and higher voltages until "all signs of gas have disappeared and the tube is backing up a 10-inch parallel spark gap and the anode is at an intense white heat."[1] Here it may be noted that the presence of harmful amounts of gas is indicated by the appearance of a greenish glow in the bulb. Should a tube which has been in use develop such an appearance it is an indica-

tion of impaired vacuum and re-exhaustion will probably be necessary.

Focusing

67. The hot filament, consisting of a piece of fine tungsten wire (0.0085″ in diameter) wrapped into a small spiral, is surrounded by a concentric cylinder of molybdenum (C, Figure 63), the inner end of which projects a little beyond the filament. At the other end of the cylinder a plane flange of molybdenum is placed. As the cylinder and flange, as well as the filament, are in electrical contact with the high tension terminal, a repulsive action is exerted on the liberated stream of electrons and focusing results. By using filaments of different shapes and adjusting the relative positions of the parts, focal spots of different sizes are obtained. In actual practice tubes with fine, medium and broad focal spots are constructed.

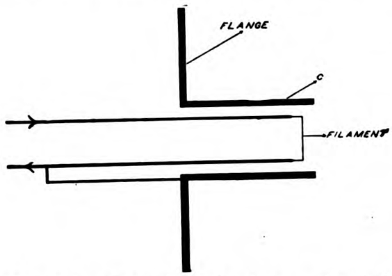

Fig. 63.—Focusing device, universal Coolidge tube.

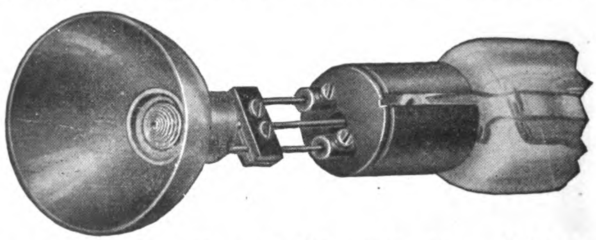

Fig. 64.—Cathode of Radiator Coolidge Tube (General Electric Co.).

The general principle of the focusing device will be clear from Figure 63. Figure 64 shows a close-up view of the cathode of the radiator type tube (Section 73), in which case the flange is replaced by a hemispherical cup.

The Anode

68. In the universal tube this consists of a solid rod of wrought tungsten attached to a stem of molybdenum.

Fig. 65.—Anode of Universal Coolidge Tube.

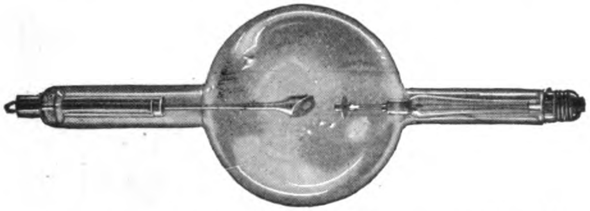

Fig. 66.—Universal Coolidge Tube (General Electric Co.).

Figure 65 renders any detailed description unnecessary. As the anode is also the anticathode, the tube has the simple appearance shown in Figure 66.

Control of Tube Current

69. In the gas tube we have seen that the residual gas is conducting, the current consisting of a stream of positive ions in one direction, along with cathode rays in the opposite direction. In the Coolidge tube the current consists solely of the stream of negative electrons liberated from the hot filament. How is the magnitude of this current controlled? In seeking to understand the answer to that question it is well to recall that an electric current is measured by the total quantity of electricity passing each second any "point" on the circuit. If, therefore, more electrons are transferred every second from the filament to the target, the tube current will be greater. Now work on thermionic

emission has shown that the higher the temperature of the hot filament the greater the supply of electrons. *The milliamperage through the tube, therefore, is increased simply by increasing the filament heating current.* But it is asked, where does voltage come in? That can be answered with reference to experimental results such as given in Tables VII and VIII (taken from Wappler Electric Co. literature). The numbers in Table VII refer to a Coolidge tube, for which the filament current is kept constant at 4.10 amperes.

TABLE VII

Filament Current 4.10 amp.

Back-up	*Ma.*
1″	13
1″	15
1¾″	18
2½″	20
3½″	21
4¼″	21
5¼″	21

TABLE VIII

Filament Current 4.20 amp.

Back-up	*Ma.*
1″	16
1″	18
1″	20
1¾″	22
2¾″	25
3¼″	25
4¼″	26
5″	26

By means of the rheostat (or auto-transformer) control, greater and greater voltages are applied to the tube, and for each value the corresponding tube current measured. It will be noticed that, while at first the tube current increases with increasing voltage, a stage is reached at which increase in voltage produces no increase in milliamperage. Those who prefer to study results in graphs rather than in tables will see that Curve A, Figure 67 shows the same result even more clearly. In Table VIII and Curve B, Figure 67, the same result is shown for a different filament current, the only difference in the two cases being that the maximum tube current in the latter is greater. Experiment tells us, then, that *corresponding to each filament current, there is a maximum value of the tube current, which is independent of the applied voltage.* The explanation of this maximum current—called the *saturation current*—is

simple enough. The available supply of electrons from a hot filament depends on its temperature and therefore on the magnitude of the filament current. Evidently no more electrons can be transported across the tube per second

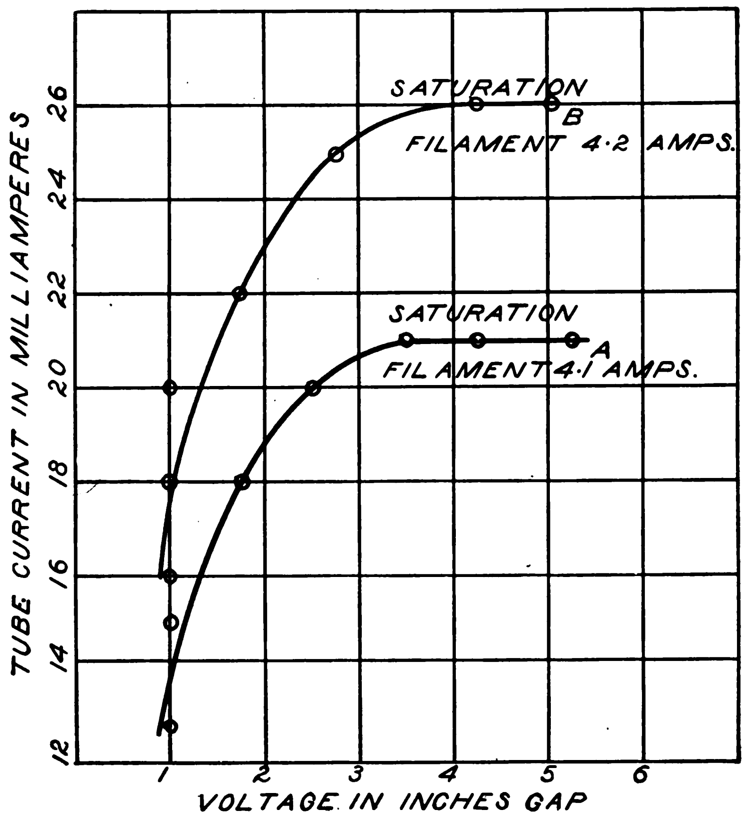

FIG. 67.—Graphs showing saturation tube current for two different filament currents.

than are liberated each second from the filament. At first, when higher and higher voltages are applied to the tube a greater and greater number of electrons is transported each second across the tube. Ultimately, however, a stage is reached at which as many electrons reach the anode per second as are liberated from the filament. Evidently fur-

ther increase of voltage cannot increase this number (although it will increase their speed) or once more, the

TABLE IX

Filament Current	*Tube Current*
3.09 amp.	0.6 ma.
3.31	2.5
3.40	4.4
3.50	8.2
3.57	12.6
3.67	20.7
3.65	21.8
3.71	27.0
4.13	35.4

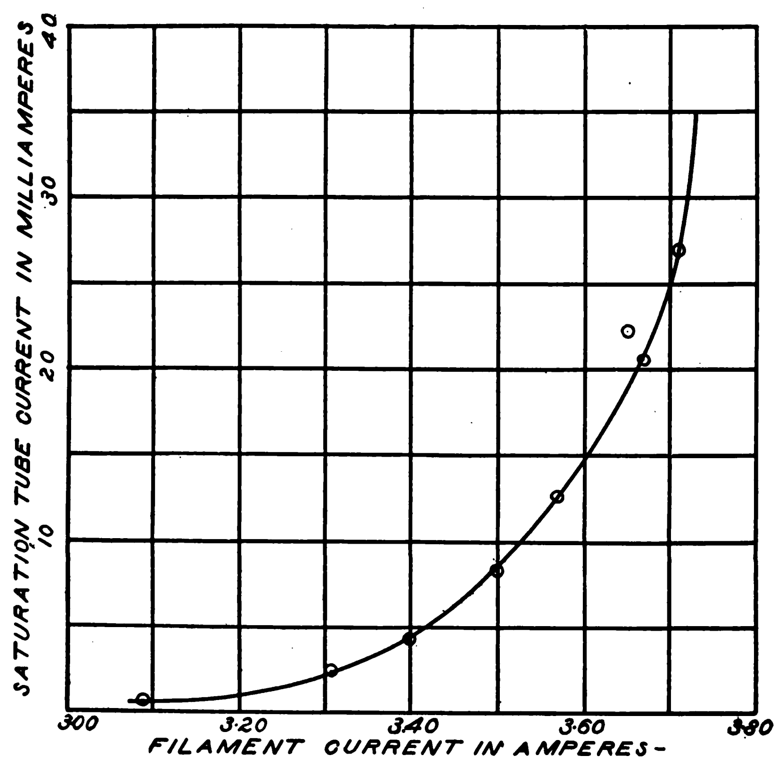

FIG. 68.—Graph showing variation of (saturated) tube current with filament current.

saturation current has been reached. In actual practice, the back-up of a tube is invariably great enough to insure the existence of saturation currents for all filament current values used.

Control of the Coolidge tube *current,* therefore, depends for all practical purposes, solely on regulation of the filament current whose magnitude is read directly from the filament ammeter. It is, then, highly desirable that the operator of a particular Coolidge tube should know the tube (saturation) current corresponding to each ammeter reading. Such a relation he can readily obtain for himself by taking, for each of several filament current values, a series of tube current values and corresponding back-ups (as in Tables VII and VIII) until the saturation stage has been reached. If, then, for each filament current, he records the saturation tube current, he will have a table similar to Table IX (a copy of some actual results taken from an early paper by Dr. W. D. Coolidge).

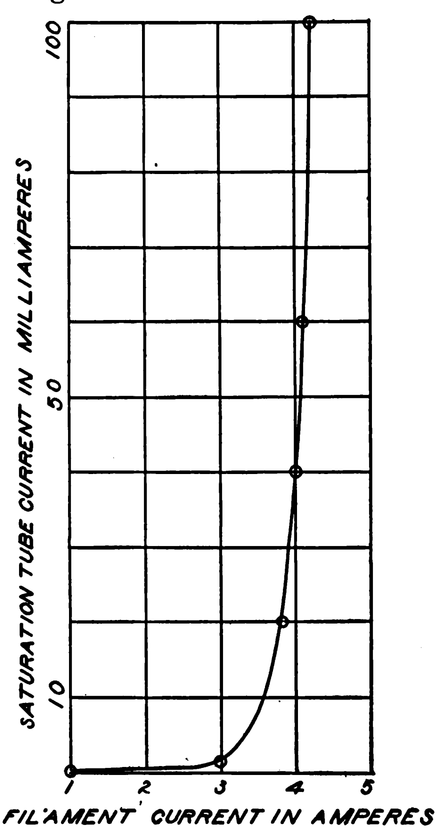

FIG. 69.—Graph showing variation of universal tube current with filament current.

By plotting these results an extremely useful curve similar to that in Figure 68 will be obtained. Figure 69 is a

copy of a similar curve for a universal tube taken from recent literature of the Victor Electric Corporation.

In the universal Coolidge tube, therefore, the tube current is controlled by the filament current and, if saturation current is used (as is nearly always the case), is independent of the voltage across the tube. (Increasing the back-up does not increase the tube current, but does alter, as we shall see later, the nature of the beam of x-rays leaving the tube.) Regulation of milliamperage and of voltage, accordingly, may be made with much greater readiness and exactness than is the case with a gas tube.

The Voltage Stabilizer

70. In connection with the relation between filament current and milliamperage it is important to note that a very slight change in the filament current may produce a big change in the tube current. To take some actual numbers from the curve of Figure 69, with filament current 4 amperes, the tube current is 40 ma., while an increase to $4\frac{1}{4}$ amperes raises the tube current to 100 ma. This has an important practical aspect. Should the filament current fluctuate, there might be marked changes in the tube current; for certain current values "a 10 per cent change in filament current will cause a 300 per cent change in the tube current." (Victor Service Suggestions.) Obviously this may have disastrous consequences.

Now, if storage batteries are used as the source of supply for the filament circuit, voltage fluctuations are negligible. Unfortunately, however, storage batteries are not so convenient as a filament transformer, and the latter is now almost entirely used. The supply for the transformer is commercial A.C., in which case voltage fluctuations are inevitable. Most readers will have observed a sudden dimming of incandescent lights when, perhaps in another

part of the house, an electric iron or toaster is turned on. The voltage applied to the lamps has lowered because of the greater "load" put on. Now, such sudden changes in voltages are almost inevitable when working with a supply used for many purposes and in many places. In using a Coolidge tube, therefore, with filament transformer and no special means for getting rid of voltage fluctuations, marked changes in milliamperage may occur.

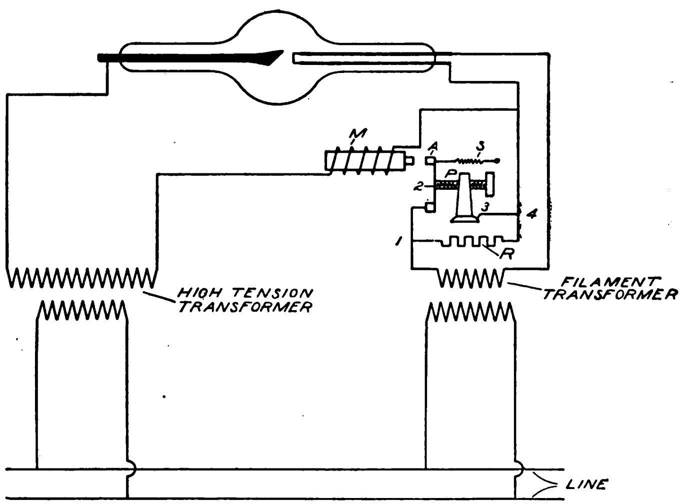

FIG. 70.—Connections for stabilizing device, to keep tube current constant.

By means of a voltage stabilizer, however, it is possible to maintain a constant tube current in spite of voltage fluctuations. The principle of one type of stabilizer [2] will be clear from a study of Figure 70. In the ordinary tube (high tension) circuit an electromagnet M is placed, near one end of which is a piece of soft iron, the armature A. When the current flows through the tube M is magnetized and the soft iron piece attracted. Before this piece moves, however, the attraction must be great enough to overcome the tension of a spring S attached to it. Evidently the greater the tension of the spring the greater the attraction

necessary to move the iron, or, in other words, the greater must be the tube current. When A is held away from the magnet (as in figure), the contact point 2 touches the fixed contact point P, so that the *filament* current flows from transformer to 1 to 2 to P to 3 to 4 through filament and back to the transformer. Should the piece A be pulled towards the magnet, however, contact between 2 and P is broken and the filament current must flow through the resistance R. There are, therefore, two possible filament circuits, one including R, which we shall call the high re-

FIG. 71.—Oscillogram showing (lower graph) constant, although intermittent, tube current obtained with stabilizer (General Electric Co.).

sistance path, the other of low resistance where R is excluded. Corresponding to these two circuits there will be (for any constant voltage) two possible values for the effective filament current, a maximum and a minimum.

To understand the action of the stabilizer it is necessary to remember that the tube current is intermittent, as is nicely shown in Figure 71, where A represents the alternating filament current, while B shows the intermittent unidirectional tube current. It follows, therefore, that even with absolutely constant voltage, until the tube current has risen to a certain critical value (which depends on the tension of the spring S), the armature is held away from the magnet. During this interval the filament current follows

the low resistance path. Once, however, the tube current exceeds the critical value the spring attraction is overcome, the armature moves toward the magnet, the contact points 2 and P are separated, the resistance R is introduced and the filament circuit has the high resistance value. During every half cycle, therefore, the contact points are together part of the time, separated the remainder of the half cycle. In other words, the armature is in a state of vibration, and the resistance of the filament circuit fluctuates between the maximum and the minimum value. Hence the effective filament current has an average value, whose magnitude depends on the fraction of the half cycle R is in or out of the circuit. If the voltage is constant this fraction remains constant, and the effective filament current is constant.

Now suppose there is a sudden rise in the voltage. This causes a momentary increase in the filament current, a greater emission of electrons, a greater tube current, a stronger electromagnet, and therefore an increase in the length of time each half cycle the contact points are kept separated due to the attraction of the armature. The filament circuit, therefore, will have the higher resistance path for a greater portion of the half cycle, and the effective filament current will be kept from rising.

On the other hand, suppose the voltage drops. A momentary drop in the filament current is followed by a lower tube current, and a feebler electromagnet, in consequence of which the armature is held away from the magnet for a longer portion of the half cycle. This time the filament circuit has the low resistance path for a longer part of the half cycle, and so the effective filament current does not drop. Thus automatically, for any given setting of the spring S, the filament current is kept constant. The efficiency of the stabilizer will be seen by a glance at Table X (taken from the article to which reference has been made) and at Figure 71. In curve B it will be seen that the

crests of the curve for the same tube current are all exactly at the same level, thus showing the constant value of the current.

TABLE X

WITHOUT STABILIZER		WITH STABILIZER	
Time	*Tube Current*	*Time*	*Tube Current*
0 Min.	10.0 ma.	0 Min.	10 ma.
½	9.6	½	10
1	9.3	1	10
1½	9.0	1½	10
2	8.7	2	10
2½	8.1	2½	10
3	7.0	3	10

IS RECTIFICATION NECESSARY?

71. In Section 64 reference has been made to the rectifying property of a hot filament tube such as the kenotron. It may well be asked, then, cannot the terminals of a high tension transformer be applied directly to the universal Coolidge tube without the necessity of a noisy synchronous motor? As a matter of fact, this can be done *provided the target is kept cool enough.* In practice, however, there is no objection to using the tube with the target extremely hot. Now, once tungsten reaches the temperature of 2000° C. (3300° C. is melting point) it begins to emit electrons. This means that, with the target above this temperature, an inverse stream of electrons is present if no rectifying device is used. Such an inverse current not only gives rise to x-rays from regions in the neighborhood of the cathode (where the inverse electrons hit), but also because of the extreme heat developed at the spot where the electrons hit, increases the danger of a tube puncture. (The danger signal in this case is the appearance of green fluorescence in the neighborhood of the cathode.) With a universal tube, therefore, a rectifying device is necessary; with

the radiator tube, however, for reasons given below, this is not the case.

Maximum Input

72. The importance of the question of permissible input should be evident from the last paragraph. As in the case of gas tubes, so in the type we are now considering, every tube has a maximum permissible input. The supply of too much energy (volts × milliamperes × time) may melt the target, vaporize the metal, blacken the tube and so increase the danger of tube puncture. Moreover, in the case of a tube used for the long intervals necessary in therapy, the heat radiated from the hot target may cause a rise in temperature of the glass bulb sufficient to liberate gas and possibly to melt the glass. Fortunately, unlike the practice in the case of gas tubes, the maximum input for each type of Coolidge tube is clearly stated. For example, in the case of the 7″ universal tube used for radiographic purposes, when operated with a voltage equivalent to a gap of 6″ between points, the milliamperage should not exceed 80 ma. for broad focus tubes, 50 ma. for medium focus, 25 ma. for fine focus. Operation on lower voltage would permit, of course, of corresponding higher milliamperage. When this same tube is used for therapeutic purposes, where the time factor may be large, an input of about one kilowatt is permissible. (1 kilowatt = 1000 watts = 10,000 volts with 100 ma., or 20,000 volts with 50 ma., etc.)

The Radiator Tube

73. In addition to the universal tube, other types based on the same general principle, are on the market. There is an 8″ bulb for high voltage deep therapy work, constructed along lines similar to the universal tube, together with at least four types of what are called radiator tubes. The four types include, (a) the right angle dental, (b) the

30 ma. straight, (c) the 10 ma. straight, (d) the 10 ma. portable. As radiator tubes may be operated directly from the transformer and have proved extremely useful, some details in connection with the 30 ma. type (Figure 72) will be considered. The essential point to realize is that no

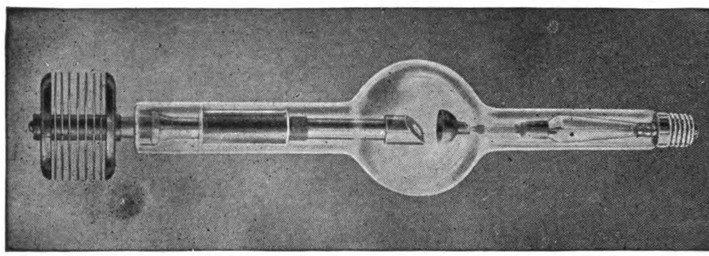

FIG. 72.—The Radiator Coolidge Tube (General Electric Co.).

rectifier is necessary because the target is never allowed to become hot enough to emit electrons. This is done, (1) by limiting the permissible input; 30 ma. must not be exceeded and that at a voltage not exceeding a 5″ back-up (between points); (2) by constructing the anode so that heat is conducted rapidly away from the focal spot.

FIG. 73.—Anode of Radiator Tube (General Electric Co.).

To prevent the rapid rise in temperature of the anode its construction differs in two important respects from that of the universal tube. A comparison of Figure 73 with Figure 65 will show the decided difference in the appearance of the two anodes. In the radiator tube, the target consists of a small button of tungsten attached to a solid

head of purified copper, which in its turn is electrically welded to a copper rod. Attached to the outer end of this rod which extends through the anode end of the glass tube, are the copper radiators clearly shown in the illustration. Now, copper is not only a better conductor of heat than tungsten but it has also a higher specific heat (see Table VI, Chapter V). For two reasons, therefore, the temperature of the radiator target rises more slowly, (1) because of its greater heat capacity, (2) because of the greater conductivity of copper as compared with tungsten, combined with the radiating device. Regarding (1) we may note that it takes only 10 calories of heat to cause a rise in temperature of the solid tungsten target (plus stem and iron support), while it takes 81 calories for the same temperature change of the radiator anode. In the radiator tube, therefore, because of the comparatively slow rate at which the temperature rises, combined with rapid cooling, an operator, when making radiographs, begins each exposure with a cool target. "With every current source it permits of the intermittent use of more energy than could in practice safely be carried by a tube with a solid tungsten target of the same size of focal spot." (Coolidge.) This means that for the same amount of energy, a smaller focal spot can be used, with consequent advantage which will be seen later. Moreover, because of the mode of radiation, a much smaller sized bulb may be used, the standard size for the 30 ma. type being 3¾″.

On the other hand, the tube for *continuous* use as in treatment will carry less than one-quarter of the energy of the universal tube. But, while it is not designed for heavy work and is recommended by Dr. Coolidge for diagnostic purposes, a 30 ma. tube with suitable transformer is an extremely useful outfit for the private practitioner. The gain which results simply from the absence of the noise of a synchronous motor and rectifying disc is in itself worth much.

A Water Cooled High Voltage Tube

73A. Recently still another type of Coolidge tube has been placed on the market,—a high power, high voltage tube. Tests by Coolidge and Moore [3] have shown that such a tube, when operated on 250,000 volts, will carry a current of 50 ma. for long time intervals. Such a large input, which is made possible by the use of a very broad focal spot and a water cooled anode, means that extremely intense beams of x-rays are now available for therapeutic work. (Section 123.)

74. In conclusion, we summarize some of the important advantages of the Coolidge tube. (1) For all types, the maximum permissible input is clearly stated; (2) the tube current (assuming saturation) is independent of the applied voltage; (3) the tube current can be regulated with the same ease as the strength of the current in any simple electric circuit; (4) by means of a stabilizer remarkably constant tube currents may be maintained for long intervals; (5) there are no vacuum troubles, provided the tube is not abused.

The Lilienfeld Tube

75. A brief reference will now be made to a third type of x-ray tube, in which, like the Coolidge, the current consists of a stream of electrons in a highly exhausted tube.[4] The tube consists essentially (Figure 74) of a pointed cathode P placed at a distance of the order of 10 mm. from a small cavity C in the target face of the anode. "The points must be grounded with the greatest care and precision on wires . . . of Wo, Ta, Mo or other refractory metals." Although the cathode is cold a liberation of electrons takes place from the pointed end, probably because of the electric field which exists betwen the cathode and anode when a high voltage is applied in the usual way. For the proper operation of this tube the vacuum must be even higher than

that necessary for a Coolidge tube, and in the initial exhaustion very elaborate precautions must be taken. For these and other details the reader is referred to the original articles.

The electrons impinge not on a plane target but on a small cavity in the face of the anode whose size depends on the amount of energy to be supplied the tube. With a plane target Dr. Lilienfeld states that there "is a tendency to form one or more extremely small focal spots," with consequent danger of melting the target. By means of the

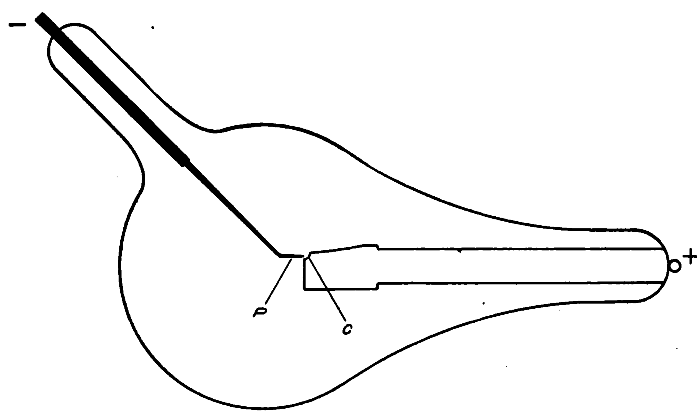

Fig. 74.—Lilienfeld X-Ray Tube.

cavity not only is the formation of very fine spots prevented by the resulting alteration in the shape of the electric field, but also use is made of secondary cathode rays generated at the spots where the primary beam strikes. In consequence, the whole cavity acts as a focal spot.

The magnitude of the tube current resulting from a given voltage depends on the sharpness of the pointed cathode, on the distance between anode and cathode, and the general geometric arrangement. Unlike the Coolidge tube, however (assuming saturation current), the tube current in this case is not independent of the voltage but rapidly increases with it. Moreover, it is claimed, the

effective voltage is confined more nearly to the crests of the wave-form than is the case with other types of tube, and for that reason (as shall be seen later) the rays are

Fig. 75.—Photograph of control stand, showing voltmeter, milliammeter, button for auto-transformer control, button for rheostat control, filament ammeter, filament control button, motor switch, and x-ray switch (Acme International X-Ray Corporation).

more homogeneous. But the tube is scarcely yet out of the experimental stage—at least as far as information at the disposal of the writer is concerned—and further details would be out of place in this book.

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1. Robinson and Moore, *Amer. Jour. of Roent.*, VII, 257, 1920.
2. Kearsley, *Amer. Jour. of Roent.*, VIII, 864, 1921.
3. Coolidge and Moore, *Amer. Jour. of Roent.*, X, 884, 1923.
4. Lilienfeld, *Amer. Jour. of Roent.*, IX, 172, 1922; Hirsch, *Jour. of Radiology,* IV, 162, 1923.

CHAPTER VII

THE PENETRATING EFFECT OF X-RAYS

General Properties of X-Rays

76. Without entering at present into a discussion regarding the nature of x-rays, we shall note certain general properties.

(1) **Photographic:** They effect a photographic plate or film in much the same way as ordinary light. The speeds of different makes vary and, for the same plate, the speed varies with the kind of rays used.

(2) **Fluorescent:** X-rays excite fluorescence in certain substances on which they fall. By fluorescence we mean the emission of visible light which continues as long as the x-rays strike the substance. Two applications of this property are made in roentgenology, the first in the use of a fluorescent screen for diagnostic work, the second in the use of intensifying screens for shortening exposures when radiographs are being made. Intensifying screens, which are made of substances such as tungstate of calcium, are placed directly in contact with the sensitive emulsion on the photographic plate or film. Wherever the rays strike the screen, therefore, the bluish (fluorescent) light emitted (which is much more actinic than x-rays) acts on the emulsion and so shortens the exposure to a marked degree. A reduction as much as five- to tenfold is quite normal. Care must be taken to keep the screen clean, for particles of dust will absorb the visible fluorescent light and spot the plate. The exposure may be still further shortened by using films sensitized on both sides along with intensi-

fying screens on each side of the film. "In actual use intensifying screens are mounted in rigid holders called cassettes, in order that perfect contact may be obtained between emulsion and screen." (Eastman Kodak Co.)

In the Impex X-ray photographic plate,[1] we have an illustration of an application of the same principle. In this plate still further reduction in the time of exposure is obtained by spreading the tungstate of the calcium on the plate itself, in a layer directly over the sensitive emulsion. By so doing, the fluorescent substances are so much more effective that reductions of the magnitude of twenty-five to thirtyfold are obtained. In using the Impex plate the only difference from the procedure with the ordinary plate lies in the necessity of washing off the fluorescent substance immediately before development.

(3) **Chemical and Dehydrating Effects.** X-rays produce a discoloration of certain alkaline salts, liberate iodine from a solution of iodoform in chloroform, and change the color of certain substances such as barium platino-cyanide.

(4) **Physiological**: The burns which result from undue exposure of the skin to x-rays, the beneficial effects of the rays on certain skin diseases, the stunting of the growth of young animals, are a few of the many examples of this important property, some further details in connection with which will be considered later.

(5) **Ionization**: X-rays make the air through which they pass conducting, as may readily be shown by placing a charged electroscope almost anywhere near a tube. On sending a current through the tube it is at once observed that the leaf of the electroscope steadily falls until the whole charge has disappeared. The rays have ionized the air in the neighborhood of the electroscope to an extent which at any given region is proportional to the rate at which the leaf falls. Should the simple experiment be repeated a number of times, each time placing the electroscope at a greater distance from the tube, it would be found that the

leaf falls more slowly the further it is removed from the tube. This indicates that the ionization at a local region (which is proportional to the rate at which the leaf falls), and so the intensity of the beam of x-rays is greater, the nearer the region is to the tube. (Sections 123, 135.)

As the ionization property is the basis of the most accurate methods of estimating dosage when x-rays are used

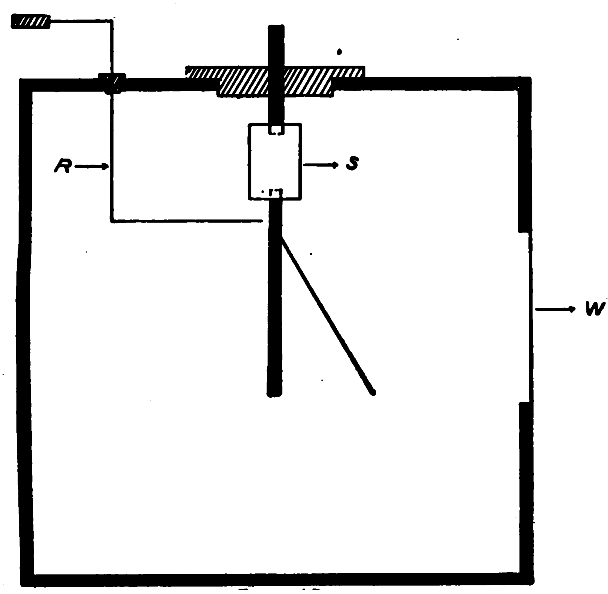

FIG. 76.—A simple electroscope for rough ionization measurements.

for treatment, the importance of this property cannot be too strongly emphasized. Later, details of suitable ionization chambers will be given; at this place, however, a simple form of electroscope which the writer has found useful in lecture experiments, may be noted (Figure 76). The leaf is attached to the usual metal support which however is supported by means of the insulating bead of sulphur S. The whole is enclosed in an earthed metal chamber in one side of which is a window W covered with very thin metal foil. The electroscope is charged by means

of a movable rod R which passes through an insulating support to the outside of the box.

(6) **Penetrating Effect**: There are few people nowadays who are not familiar with the fact that x-rays pass through fairly thick sheets of matter which we ordinarily call opaque. A thin piece of wood is almost as transparent to x-rays as window glass is to sunlight. But thin layers of any substance are more transparent than thick, and some substances are more opaque than others; and herein lies the basis of the familiar x-ray pictures. Radiographs are just shadow pictures, wherein detail is visible because of the unequal degree to which different parts of the subject photographed absorb x-rays. There are in consequence corresponding differences in density on the plate or film. As the whole application of x-rays both for radiography and for treatment is bound up with the question of absorption of x-rays, the question of penetrating power will now be considered in detail.

77. It is first of all important to realize that the terms opacity, or opaqueness, or transparency, of a substance to x-rays are very indefinite. An experimental illustration will make the point clearer. Before the window of a charged electroscope (Figure 76) is hung a sheet of so-called protective rubber. On placing a small x-ray tube a short distance away with its target pointing towards the window of the electroscope it is found that, when the tube is running on moderate voltage, the leaf of the electroscope remains stationary or falls extremely slowly. On using a larger tube, however, operated at higher voltage, the leaf falls in a matter of a few seconds. The rubber is opaque to the first beam of x-rays, but far from it to the second. In other words, x-rays from some tubes are more penetrating than from others.

78. Again, the same bulb when operated under different conditions emits rays which have different penetrating effects. Suppose a Coolidge tube is used, with always the

same milliamperage, but at a series of different voltages. Suppose, further, that for each voltage the distance of the tube from the electroscope is adjusted so that in each case the leaf falls at the same rate, when the sheet of rubber is absent. If now another set of readings is taken for each voltage, with corresponding distances, with the rubber sheet interposed, it is found that the higher the voltage the more rapidly the leaf falls. The conclusion is obvious—the higher the voltage across a tube the more penetrating the rays emitted.

There are, therefore, different kinds of x-rays which we may describe as *hard, medium,* or *soft,* according as they are very penetrating, moderately penetrating or feebly penetrating. It will be recalled (Section 49) that the same terms are used to describe the state of a gas tube, a hard tube being one for which a higher voltage is required to maintain a certain current than is the case with a soft one. But there is no confusion of terms, for we have just seen that a higher voltage across a tube means an increase in the penetrating power of the rays emitted. A hard tube, therefore, emits an excess of hard rays, a soft tube an excess of soft rays. But the terms hard, medium and soft are much too elastic for the accurate measurement of so important a quantity as the penetrating power and we must seek some means of expressing degrees of hardness by definite numbers. In other words, we need a scale in terms of which the *quality* of a beam of x-rays may be expressed.

Means of Measuring Quality

79. Four different methods may be used: (1) Method I, involving a measurement of the voltage across the tube; (2) Method II, in which (a) it is necessary to determine the thickness of some standard substance required to reduce the intensity of a beam by 50 per cent, or, (b) the intensity of a beam is measured before and after the insertion of a

standard thickness of a standard substance; (3) Method III, in which the absorption of rays by two different metals is compared; (4) Method IV, by the direct measurement of the wave-lengths in the beam or of the so-called "effective" wave-length. Each of these methods will be considered in turn.

Hardness by Spark Gap and Bauer Qualimeter

80. Since, as we have pointed out, the penetration increases with the voltage across a tube, the length of the equivalent spark gap may be taken as at least a rough measure of the degree of hardness of the rays leaving a tube. The longer the gap, the harder the rays. (See Table XIV.)

81. In the Bauer Qualimeter we find a practical instrument which utilizes this same principle. It is an electrostatic voltmeter which is used somewhat like the voltmeter described in Section 19, and therefore may be placed at any convenient place in the x-ray room. The instrument consists essentially of two fixed plates between which two vanes are free to move. As the higher the potential the greater the deflection of the movable vanes this deflection is taken as a measure of the hardness of the rays leaving the tube. A pointer attached to the vanes moves over a scale from which the hardness is read, not in "inches or centimeters of spark-gap," but in a purely arbitrary scale with numbers running from 1 to 10. Number 1 indicates a penetration such that the corresponding rays are completely absorbed by 0.1 mm. of lead, number 2 by 0.2 mm. of lead, and so on until we reach number 10 indicating rays completely absorbed by 1 mm. of lead. Numbers 4, 5 and 6 correspond to medium rays, smaller numbers to soft, higher to hard rays.

In the Bauer Qualimeter, therefore, we have the first kind of *penetrometer* which has been used to express the

degree of penetration by a definite number. Its usefulness, however, is limited for several reasons. (a) Two bulbs, with exactly the same back-up, will not always emit rays of the same degree of hardness. (b) Again, the hardness of what are called characteristic x-rays (to be discussed later) does not increase steadily with the applied potential. (c) Layers of some absorbing substance are frequently placed between the tube and the place "treated," and these filters, as they are called, alter the mean quality of the rays. It is desirable, therefore, to use more direct means of measuring the penetration, such as we have in Method II.

Hardness by Half Thickness Method

82. To use this method, layers of increasing thickness of some standard substance are interposed between the x-ray tube and some measuring instrument such as the electroscope, and the particular thickness determined which reduces the intensity of the beam exactly 50 per cent. This thickness, which is called the *Half Absorption Value,* is clearly a measure of the hardness of the rays. The choice of a suitable standard substance depends on several factors, but for work in radiology it is decidedly advantageous to use a substance whose absorption can be compared with that of body tissue. For that reason aluminium, water, and

Table XI

Thickness of Aluminium	*Intensity of Radiation*
0	100
1	68.6
2	51.3
3	39.9
4	32.4
5	29.0
6	25.4
7	21.7
8	19.4
9	16.8
10	15.0

bakelit * have been used, although it will be seen later that aluminium is not satisfactory from this point of view.

83. In Table XI is given a typical set of readings due to Kroenig and Friedrich [2] showing the gradual reduction

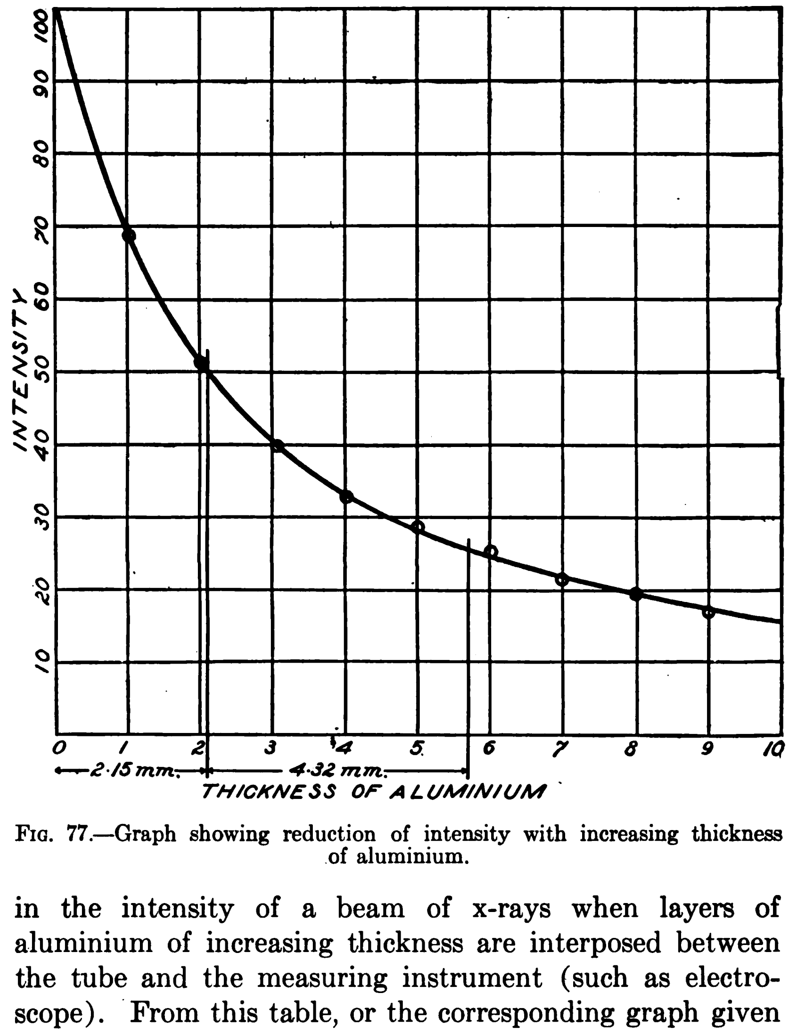

FIG. 77.—Graph showing reduction of intensity with increasing thickness of aluminium.

in the intensity of a beam of x-rays when layers of aluminium of increasing thickness are interposed between the tube and the measuring instrument (such as electroscope). From this table, or the corresponding graph given

* Bakelit is an insulating material made by hot pressing paper or cloth with raw bakelit, a condensation product of phenol and formaldehyde.

in Figure 77, it is easy to find out that the value of D, the thickness necessary to reduce the intensity from 100 units to 50 units is 2.15 mm. But if we attempt to describe the quality of the rays leaving this tube by stating that their half absorption value is equal to 2.15 mm. of aluminium, we encounter a difficulty. The same table (or graph) shows that the thickness necessary to reduce the intensity from 50 to 25 units, that is a second 50 per cent, is not 2.15 mm., as might be expected, but 4.32 mm. *Evidently the penetrating power of the rays after having transversed the first few layers has increased.* The conclusion is obvious—the original beam must have contained a mixture of rays, some more penetrating than others. The first absorbing layers therefore removed a great percentage of the softer, less penetrating rays, thus transmitting a beam with an excess of harder rays. Now as we shall see again later, the same can be shown with reference to the beam of x-rays leaving any tube—there is always a mixture of both hard and soft rays. Stepping up the voltage increases the average penetrating power, but there are always soft rays present.

FILTERS

84. Because of the fact which has been emphasized in the previous section, it is often necessary to get rid of the softer components. Suppose, for example, deep-seated tissue were being treated with x-rays which of necessity would have to be very penetrating. In such a case the soft rays present would be almost completely absorbed by the skin and intervening tissue, and more harm than good might be done. To remove the soft rays, filters are used, that is, layers of some substance placed between the tube and the place treated. For protecting the skin from very feeble rays, substances such as aluminium, paper, tanned leather, chamois leather, felt, lead acetate lint and sodium acetate lint, are sometimes used. Metallic filters of greater

absorption are also used, when it is desired to obtain a beam of fairly homogeneous hard rays. The effect of filters for this purpose will be clear from an inspection of Table XII (Kroenig and Friedrich).[2]

TABLE XII

Quality	*Filter*	*D for first 50 per cent*	*D for second 50 per cent*
1	None	1.8 cm.	2.25 cm.
2	3 mm. Al.	2.4 cm.	2.65 cm.
3	10 mm. Al.	3.25 cm.	3.30 cm.
4	1 mm. Cu.	3.7 cm.	3.75 cm.

This table gives the thickness of water necessary to reduce the intensity of four different beams of x-rays of increasing hardness: (1) from 100 to 50 units, (2) from 50 to 25 units, with different conditions of filtration. The table shows that rays which have been filtered with 10 mm. of aluminium or still better, 1 mm. of copper, are approximately homogeneous, that is, successive reductions in intensity *of equal amounts* are produced *by equal thicknesses* of an absorbing medium. Such filters completely absorb the softer components.

In such cases the value of D is a fairly accurate measure of the quality of the rays utilized. Even in the case of rays which are far from homogeneous, the half absorption value gives a good idea of the average penetrating power of the beam. For example, rays which have a value of D in the neighborhood of 10 mm. of aluminium are of average hardness; values considerably greater correspond to very hard rays, considerably less to very soft. Thus, if the same absorbing medium is always used, the values of D obtained for different beams of rays provide a set of numbers for comparing their average penetrating powers. The larger D, the more penetrating the rays. (In Section 111 a more detailed discussion of filters will be given.)

The Christen Penetrometer

85. It is not always necessary, however, actually to have an ionization instrument and to make intensity measurements similar to those given in Table XI. There are other types of penetrometers for enabling an operator in a very few minutes to obtain at least an approximate value of the penetration. In the Christen penetrometer, for example, the quality is expressed in terms of the half thickness value of bakelit. The beam whose penetration is to be measured falls on a fluorescent screen, after one portion has passed through a perforated lead plate, and another through a bakelit step ladder (wedge). The lead plate contains small holes of such an area that the intensity of the beam is reduced exactly one-half. In actual use a reading is taken of the particular thickness of the bakelit wedge behind which the intensity of the fluorescent light is the same as that behind the lead plate. Obviously this is the required half absorption value, and the quality is at once expressed in terms of this thickness.

A brief reference will now be made to a few other penetrometers in all of which penetration is measured by means of the third method, that is, by a comparison of the absorption of different metals.

The Benoist Penetrometer

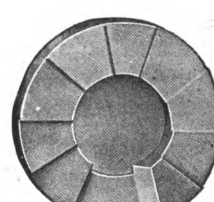

Fig. 78.—A Benoist Penetrometer (Wappler Electric Co.).

86. This consists (Figure 78) of a disc about an inch or more in diameter, with a central ring of thin silver, 0.11 mm. thick, surrounded by 10 or 12 sectors of aluminium with thicknesses ranging from 1 mm. to 10 or 12 mm. The general appearance is somewhat like that of a spiral staircase. In actual use the penetrometer is placed directly over a photographic plate. As each section of the corresponding image obtained on development is blackened

an amount which depends on the extent to which rays are absorbed, there is one sector whose image shows the same shade or degree of blackening as that behind the silver center. Should the rays be made more penetrating, a thicker sector would have the same shade. Figure 79 is a reproduction of an actual photograph, for the use of which

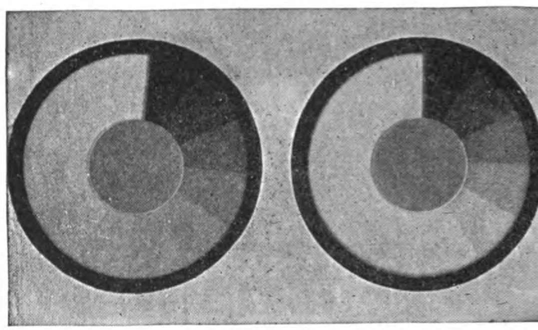

FIG. 79.—Photographs with Benoist Penetrometer (General Electric Co.).

my thanks are due Dr. W. D. Coolidge. As the number of the sector which shows the same shade as the inner circle is taken as a measure of the penetrating power, we are provided with another arbitrary scale of quality, Benoist 1, 2, 3,—to 10 or 12. Benoist, number 6 (B.6) for example, corresponds to a medium degree of hardness. This penetrometer depends on the principle that silver absorbs strongly practically all kinds of x-rays used in radiology. (Section 111.)

THE WATER RADIOMETER

87. This consists essentially of a sheet of lead, perforated with eight holes, each of which is covered with a sheet of platinum, and the whole backed with a fluorescent screen. As the thickness of the pieces of platinum vary in geometrical progression from .005 mm. for hole No. 1 to .64 mm. for hole No. 8, the more penetrating the rays the greater will

be the number of fluorescent spots observed on the screen.

The degree of hardness is therefore measured by the number of the hole corresponding to the greatest thickness of platinum penetrated.

The Wehnelt Crypto-Radiometer

88. In principle this is similar to the Benoist Penetrometer. Behind a lead plate with a vertical slit is placed a fluorescent screen. In front of the slit is placed a flat strip of silver and a *wedge* shaped strip of aluminium, both of which may be slid along in a horizontal direction. Rays falling on this radiometer pass through the silver and the aluminium, thus causing the screen behind the vertical slit to fluoresce. The penetration is measured in terms of the thickness of the aluminium wedge behind which the intensity of fluorescence is equal to that behind the silver.

89. As the use of both the Walter and the Wehnelt penetrometers depends on visual observation of a fluorescent screen, it should be evident that care should be exercised that the lead plate provides ample protection for the observer. (See Section 91.)

Comparative Values of Various Penetrometers

90. As in the different means of measuring penetration which we have been discussing, purely arbitrary scales are used, it is highly important to be able to compare one scale with another. For example, in the Wehnelt scale, what

Table XIII

Table of Comparative Values of Various Penetrometers (After Knox).

	Soft			*Medium*				*Hard*		
Bauer	1	2	3	4	5	6	7	8	9	10
Wehnelt	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15
Walter	1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	..	..
Benoist	1	2	3	4	5	6	7	8	9	10

corresponds to Benoist 7? The answer will be found in Tables XIII and XIV in which comparative values are given, one set after Knox, the other after Christen.

TABLE XIV

TABLE OF COMPARATIVE VALUES OF VARIOUS PENETROMETERS (AFTER CHRISTEN).

Half-Value Layer in cm.	*Wehnelt*	*Benoist*	*Walter*	*Bauer*	*Spark gap in cm.*
0.2	1.7	1	..	1.1	1–4
0.4	3.2	3	4	2.2	3–6
0.6	4.8	4	5	3.2	5–10
0.8	6.2	4	5	4.1	6–12
1.0	7.5	5	6	5.0	7–15
1.2	8.8	6	7	5.8	8–18
1.4	9.8	7	8	6.5	12–25
1.6	10.6	8	8	7.1	...
1.8	11.3	8	..	7.5	...
2.0	11.9	9	..	7.9	...

PROTECTION

91. Before discussing the fourth method of measuring penetration, we shall digress briefly to discuss the subject of Protection. We have seen that with increasing voltage goes an increase in the penetration of the rays emitted by a tube. In other words, as we have already noted, a substance may be absolutely opaque to rays from a tube on low voltage, and comparatively transparent when much higher potentials are utilized. With the high voltage machines now available, it is possible to obtain x-rays which will penetrate 4 to 5 mm. of lead, or 7.5 cm. of steel or iron. Indeed we have an industrial application in the use of x-rays to detect the presence of flaws in steel plates, copper castings, etc. It follows, therefore, that with the increasing use of higher voltages, both in industry and in radiology, the importance of exercising the utmost care to guard against undue exposure to x-rays cannot be too strongly emphasized. The penalty which so many pioneer workers

had to pay for (in their case) excusable ignorance of the dangers, should be a warning to all beginners in x-ray work.

Protection is necessary not only because of damage of burns and allied troubles resulting from undue exposure to the rays, but also because of the danger of contact with high tension wires and apparatus, as well as from noxious fumes developed in the x-ray room. What some of the necessary precautions are, may best be given by quoting from the report of the X-Ray and Radium Protection Committee of Great Britain.[3]

Ventilation

"1. It is strongly recommended that the X-Ray Department should not be below the ground level.

"2. The importance of adequate ventilation in both operating and dark rooms is supreme. Artificial ventilation is recommended in most cases. With very high potentials coronal discharges are difficult to avoid, and these produce ozone and nitrous fumes, both of which are prejudicial to the operator. Dark rooms should be capable of being readily opened up to sunshine and fresh air when not in use. The walls and ceilings of dark rooms are best painted some more cheerful hue than black."

Electrical Precautions

"The following recommendations are made:

"1. Wooden, cork, or rubber floors should be provided; existing concrete floors should be covered with one of the above materials.

"2. Stout metal tubes or rods should, wherever possible, be used instead of wires for conductors. Thickly insulated wire is preferable to bare wire. Slack or looped wires are to be avoided.

"3. All metal parts of the apparatus and room to be efficiently earthed.

"4. All main and supply switches should be very distinctly indicated. Wherever possible double-pole switches should be used in preference to single-pole. Fuses no heavier than necessary for the purpose in hand should be used. Unemployed leads to the high tension generator should not be permitted."

Deep Therapy

"This section refers to sets of apparatus giving voltages above 100,000.

"1. Small cubicles are not recommended.

"2. A large, lofty, well ventilated and lighted room to be provided.

"3. The x-ray bulb to be enclosed as completely as possible with protective material equivalent to not less than 3 mm. of lead.

"4. A separate enclosure to be provided for the operator, situated as far as possible from the x-ray bulb. All controls to be within this enclosure, the walls and windows of which to be of material equivalent to not less than 3 mm. of lead."

Full details will be found in the original report.

Where transparency (for visual observation) or flexibility is required, sheets of lead glass or of rubber impregnated with lead may replace lead itself. Such sheets should be considerably thicker than the corresponding minimum layers of lead; in the case of good rubber, from 2 to 4 times as thick, in the case of glass from 5 to 10. Different specimens vary considerably, however. Ultimately it is probable that such material will have to be sold with the standardization mark of the Bureau of Standards, or, in England, of the National Physical Laboratory. It should not be forgotten, too, that rubber deteriorates with age, and should be renewed periodically.

The x-ray tube itself should always be covered with protective material except for a small opening through

which the beam to be utilized can pass. In addition to the permanent protective shield usually found about a bulb, an extra protective layer of rubber as described by Pfahler [4] may well be used.

PENETRATION AND WAVE LENGTH

92. The most exact way of describing the quality of a beam of x-rays is found in the fourth method, that is, by giving the wave-length or the effective wave-length of the beam utilized. Before this method can be disclosed, however, it is necessary to say something about the nature of x-rays.

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3. Preliminary Report of the X-Ray and Radium Protection Committee. Pfahler, *Amer. Jour. of Roent.*, IX, 803, 1922.
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CHAPTER VIII

THE NATURE OF X-RAYS

93. For many years after their discovery by Roentgen in 1895, the exact nature of x-rays was a subject about which there was much speculation. Although Roentgen himself thought of the new rays as a wave phenomenon, it was not until 1912 that conclusive evidence concerning their nature was given. In that year, however, as a result of the work of Laue, assisted by Friedrich and Knipping, it was experimentally demonstrated that the phenomenon of interference could be obtained with x-rays, and that consequently they were without doubt a form of wave-motion. As the pioneer work of these men opened up a field of research which has led to tremendous advances in our knowledge both of x-rays and of other physical phenomena, it is desirable that all x-ray workers should clearly understand the fundamental ideas of wave-motion.

Everyone is familiar with water waves, as well as with the fact that they may be big, or very "tiny" as in the case of what we ordinarily call ripples. An observer watching water waves at all carefully cannot fail to be struck with two things: (1) crests and troughs repeat at regular intervals; (2) at any place on which he may fix his attention, the water goes through a to and fro motion; a floating block of wood bobs up and down, up and down, and so on. Now these two features are characteristic of any regular train of waves. At any given instant (imagine a snapshot photograph taken) the position of particles is repeated at regular intervals, which we call wave-lengths. A wave-length, therefore, is the distance between successive particles whose

displacement and velocity with reference to their normal position is the same, or to use the technical phrase, two particles which are in the same phase. In the case of water-waves, from crest to crest, or trough to trough, is a wave-length. On the other hand, if we fix our attention on the particles at any particular place, we see that each particle at regular *time* intervals, comes back to the same position. This time interval is what is called the *periodic* time or briefly the period, although more often we speak of the *frequency* or the number of complete to and fro vibrations per second.

It is not a difficult matter to prove that the wave-length is also the distance the wave disturbance travels during the time of one complete vibration of a particle.

94. In sound waves we have exactly the same phenomena. As a train of sound waves travels along, the air particles at all places go through a to and fro motion. If we could take a snap-shot of the air, we should be able to see that certain particles, separated by regular intervals, are displaced exactly the same amount from their normal position. Should we take a set of tuning forks all of which vibrate at different rates we should observe something else, and that is, that the wave-length is shorter the more rapidly a fork is vibrating. Now everyone knows that a person listening to such a set of tuning forks would hear for each one a characteristic note of a musical scale. From what has just been stated, however, it should be evident that physically we can describe the different notes by giving either the frequency of the fork (number of vibrations per second) or the wave-length emitted. The higher the pitch of the note, the higher the frequency, the shorter the wave-length. In sound usually we make use of frequency, but it is important to realize that we might describe different notes in terms of corresponding wave-lengths.

95. In ordinary (visible) light we have another important example of wave-motion. In this case the medium in

which the vibrations take place is the invisible "luminiferous" ether. To visualize what is going on one may think of vibrations of ether "particles," or may make use of the modern conception that light-waves are electromagnetic in character. On this point of view, when a train of light waves passes along there is, (1) at any place, a periodic change in the electric and magnetic intensity, while (2) at any instant (compare the snap-shot above) the values of the electric and magnetic intensity repeat at regular intervals, which we call the wave-length. Moreover, just as in sound we have different frequencies and wave-lengths, so in light we have different colors. These also we describe physically in terms of corresponding frequencies or wave-lengths. Although it is not always the case, in light it is more usual to use wave-lengths. To come to definite numbers, when waves of lengths ranging from approximately 0.00007 cm. to 0.00006 cm. fall on the eye, the sensation of red results. Physically wave-length 0.000068 cm. is not the same red as, say 0.000065 cm. but the eye probably would not be able to detect any difference. Wave-lengths in the neighborhood of 0.000058 cm. correspond to yellow, and so on down through the ordinary spectrum until we come to violet, corresponding to wave-lengths a little greater than 0.000040 cm.

96. But light-waves are not the only ether waves with which we have to deal. There are waves longer than the longest red, and shorter than the shortest violet. On the long side we have first of all what is called the infra-red region, comprising wave-lengths ranging from 0.00007 cm. to .031 cm. These waves, at least the shorter of them, are sometimes called heat-waves because on absorption by a body on which they fall they give rise to a considerable amount of heat. The name, however, is not a happy one, as shorter waves also on absorption give rise to heat.

Next we have the still longer electrical waves which have

lengths nearly * as short as the longest infra-red, and as long as those used in wireless. In "Radio," for example, wave-lengths of the order of several hundred meters are used, while we may have electric waves even miles in length.

97. Turning to the other end of the spectrum, we find first of all the ultraviolet region comprising waves which, but a few years ago, ended at 0.00001 cm. but which in the last year or two have been obtained as short as 0.000002 cm. In ultraviolet therapy use is made of the waves in this region from approximately 0.00004 cm. to 0.00002 cm. In passing we may note that these short waves are very easily absorbed by matter, a thickness as small as 1 mm. of air at atmospheric pressure absorbing beyond 0.000017 cm. For the measurement of the extremely short waves in this region apparatus with air at very low pressure must be used. Glass itself is transparent only to waves a little beyond the visible violet, and, for that reason, quartz (opaque beyond 0.0000185 cm.) must be used in lamps designed for their ultraviolet output.

Coming to x-rays, we have seen that the work of Laue, Friedrich and Knipping showed that these also are ether waves, usually of wave-lengths much shorter than even the shortest ultraviolet. While the complete range extends from 0.000005 cm. to 0.0000000006 cm., in radiology the rays utilized have lengths ranging from 0.000000003 to 0.0000000006 cm. Finally we have gamma rays of radium, the shortest known ether waves, with wave-lengths ranging from 0.000000014 to 0.0000000001 cm.

The Angstrom

98. Because of the extreme shortness of both visible and invisible light waves, another unit of length is generally

* The writer understands that as a result of recent work the gap between the electrical and infra-red region has been bridged.

used. This new unit, which is called the Angstrom, is simply 10^{-8} cm., that is, one hundred millionth of a centimeter. Thus instead of writing 0.00006 cm. we write 6000 angstroms or 6000 A.U. and the range of wave-lengths used in radiology (as given in Table XV) extends from 0.3 A.U. to 0.06AU. Table XV gives a summary of all classes of ether waves with approximate limits, while Figure 80 shows graphically (logarithmic scale) the complete range. It should be clearly understood that, although one class is called electrical, all these waves are of the same character, all electromagnetic. Differences in their properties correspond solely to differences in their wave-lengths. In the next chapter

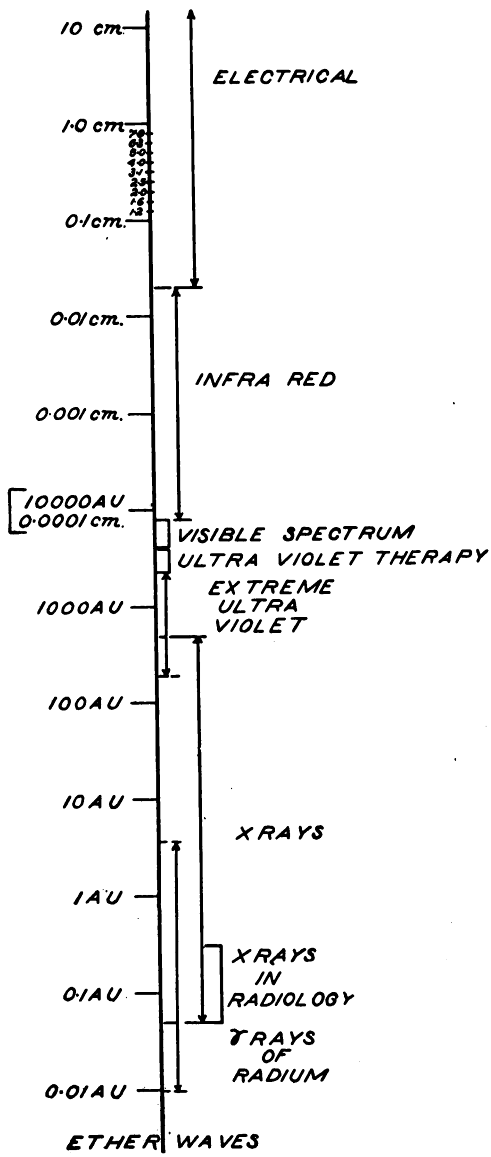

FIG. 80.—Graphical representation of complete range of wave-lengths.

questions of penetration and wave-length will be discussed and a brief reference will be made to the method of measuring x-ray wave-lengths.

TABLE XV

	Range of Wave Lengths
Electrical	10^6 to 0.08 cm.
Infra-red	0.031 cm. to 0.00007 cm.
Visible	0.00007 cm.–0.00004 cm. 7000 A. U.–4000 A. U.
Ultraviolet	4000 A. U.–2000 A. U.
Extreme ultraviolet	4000 A. U.– 200 A. U.
X-Rays	500 A. U.–0.06 A. U.
X-Rays in Radiology	0.3 A. U.–0.06 A. U.
Gamma Rays of Radium	1.4 A. U.–0.01 A. U.

CHAPTER IX

MEASUREMENT OF WAVE-LENGTH

99. It should now be evident that for an accurate description of the character of x-rays, the terms hard, medium and soft are extremely vague. Penetration depends on the wave-length and the only accurate method of stating the quality of a beam of x-rays is to give its wave-length or the range of wave-lengths which it contains. Should the range be very limited, the beam may be considered *homogeneous* or *monochromatic;* if a wide range is covered, heterogeneous. An analogy from ordinary light will perhaps be useful. A beam of white light from the sun or an incandescent lamp is very heterogeneous, analysis by a spectroscope showing it to be a mixture of wave-lengths covering a wide range (all, however, very much longer than x-rays). On the other hand, if a piece of pure red glass is placed in the path of the white beam, the light emerging from the glass is approximately homogeneous. We call it a red beam, but might better describe it by saying the mean wave-length is in the neighborhood of 6200 A.U.

In radiology, therefore, it is of the utmost importance to know what kind of x-rays are being used. In treatment especially real advances are only possible by the use of homogeneous rays whose effective wave-length is known. Fortunately advances of the last few years are making it an easy matter for medical men to make the necessary measurements. Comparatively simple x-ray spectrometers or spectrographs are now on the market by means of which direct readings of wave-lengths are readily made. For the intelligent use of such instruments, however, it is necessary

to know something of the principles on which they are based. In the following paragraphs a brief explanation of these is given.

Reflection of Waves

100. All readers are familiar with the fact that a beam of ordinary light such as AB, Figure 81, is regularly reflected

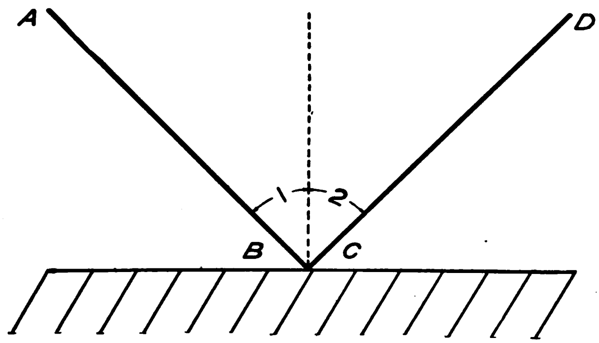

Fig. 81.—Regular reflection of a narrow beam of light.

by a mirror along the path CD, in such a direction that the angle 1 is equal to the angle 2. (Angle of incidence = angle

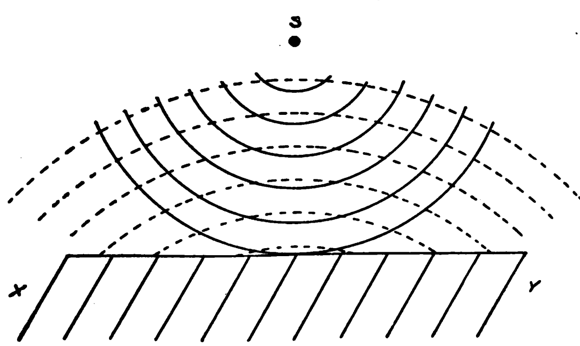

Fig. 82.—Regular reflection of circular waves at plane surface.

of reflection.) Now such regular reflection is true for any kind of wave-motion provided the surface of the reflector is smooth. By "smooth" is meant a surface with irregulari-

ties which are of the same order or smaller than the length of the waves. If circular waves on the surface of water spread out from a source S, Figure 82, until they strike a smooth wall at XY, they are regularly reflected in a manner indicated by the dotted lines. Again, if what we call plane water waves strike a reflecting surface obliquely as in Figure 83, the waves are again regularly reflected as illustrated. It will be seen that this case is exactly similar to that illustrated in Figure 81.

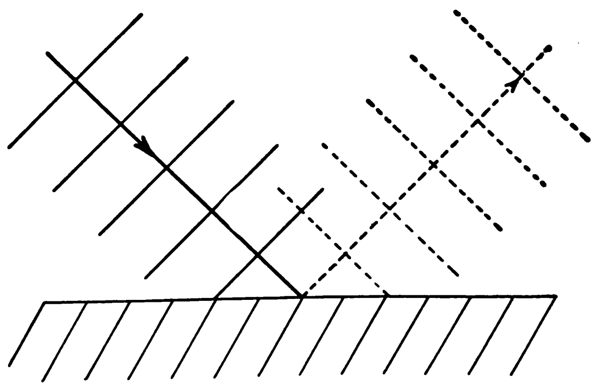

FIG. 83.—Regular reflection of plane waves at a plane surface.

101. The important question now arises, Is a beam of x-rays reflected in the same way? Before 1913 experiments to answer that question all gave a negative answer, for a reason which should now be evident. The lengths of x-ray waves are so short that it is not possible to manufacture a smooth enough mirror. The irregularities of even the smoothest surface made are large compared with the wave-lengths of x-rays and regular reflection in the ordinary sense is not possible. But what man cannot do, Nature sometimes can, and this proved to be true in the case of x-rays. The regular arrangement of atoms in a natural cleavage plane of a crystal provided the necessary "smooth" reflect-

ing surface.* Once Laue had proved by means of a crystal that x-rays were ether waves it remained for the fruitful genius of the Braggs to establish the use of cleavage planes of crystals as reflectors, and so to open up a field of investigation which now includes many workers. One direct result of the pioneer work of the Braggs is the x-ray spectrometer.

THE X-RAY SPECTROMETER

102. To understand the fundamental principles on which this instrument is based, it is necessary first of all to realize that the reflection of x-rays from the face of a crystal is not exactly the same as the cases described in Section 100. Since x-rays penetrate matter, *we have to do with a series*

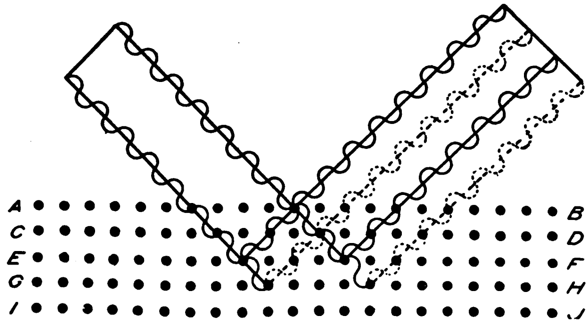

FIG. 84.—Reflection of x-rays from successive parallel planes of atoms.

of reflections from successive parallel planes of atoms. A glance at Figure 84 will help to make the matter clearer. In this figure the rows AB, CD, EF, etc., represent a simple arrangement of atoms in successive parallel planes. If now a beam of x-rays is incident as shown, there will be reflected beams from AB, CD, EF, etc. (in the figure an attempt is made to show reflected beams from EF and GH), and it is natural to ask, Will all these beams unite to form a single

* Because in a cleavage plane of a crystal we have to deal with a sort of lattice arrangement of atoms and "spaces" alternating, the reflection of which we speak is not exactly the same as that of ordinary light from a mirror.

intense beam? In general *they do not* and herein lies the basis of the measurement of x-ray wave-lengths. To understand the reason something must be said about the principle of interference.

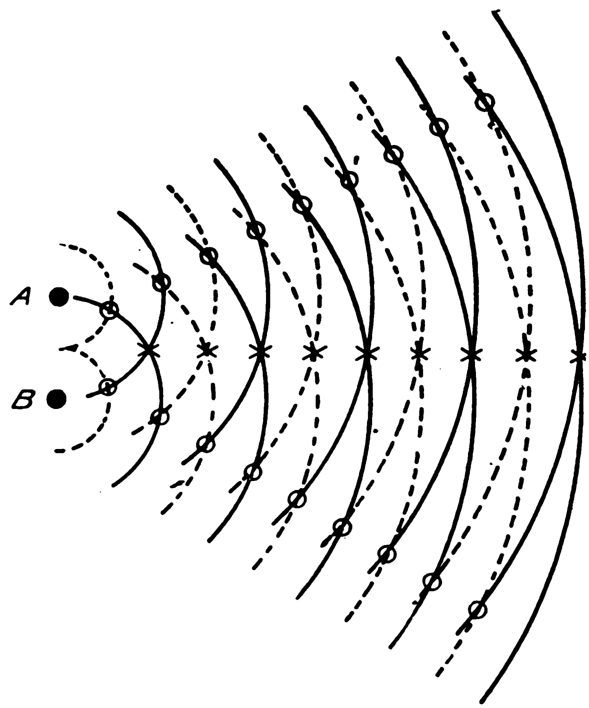

FIG. 85.—Two sets of circular waves from two sources.

103. If two stones are thrown into a pond, at A and B (Figure 85), it is a matter of common observation that the resulting sets of circular waves travel through each other. The illustration, therefore, represents a snapshot picture of the surface of water, heavy lines indicating crests of waves, dotted lines troughs. It will at once be noticed that at all points marked *o*, a crest from A arrives at the same time as a trough from B, and that consequently at such points *the surface of the water remains in its normal position.* At other points marked *x* a crest (or a trough) from

one source is always met by a crest (or trough) from the other, with the result that at these places there is a big movement of the water. In other words, *at some places the effect of one wave train may annul the effect of another, while at other places the two sets may reinforce each other.* This is the important principle of interference. Suppose, now, we are dealing with a beam of homogeneous x-rays. If Figure 84 is examined again, it will be seen that waves reflected at GH have to travel a path which is longer than the path of those reflected at EF; similarly waves reflected at AB a path longer (by an equal amount) than waves from CD, and so on. If this path difference is *exactly* equal to the wave-length of the rays, crests of one reflected beam will always meet the crests of another, and consequently all the beams will reinforce each other. In other words, when this is the case the total intensity of the reflected beam will be very great. In general, however, the path difference will *not* be exactly equal to one wave-length and the intensity of the reflected beam is very feeble. The importance of this point can scarcely be overemphasized. *It means that when a beam of homogeneous x-rays is incident on the face of a crystal, there is a reflected beam of marked intensity only when the path difference between the beams reflected from any two successive planes is exactly one wave-length.** Should a heterogenous beam be incident on the face of the crystal at any given angle, as in Figure 86, it follows that there will be an intense beam in the usual

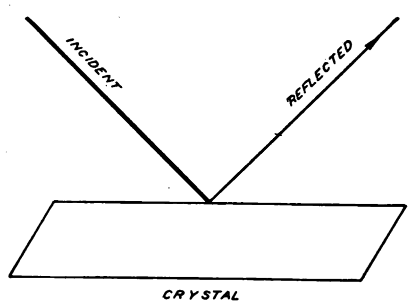

FIG. 86.—Regular reflection of x-rays from a crystal, for a monochromatic beam.

* This will also be the case for path differences exactly equal to two, three, etc., wave-lengths.

reflected direction (Angle of incidence = angle of reflection) *only for that component* of the mixed beam for which the path difference is one wave-length. This path difference, therefore, is a very important quantity. It can easily be shown that its value depends on, (1) the angle which the beam makes with the face of the crystal, (2) the distance between successive planes of the crystal.*

As for any given crystal the distance between successive planes is a fixed quantity, it follows that when a beam of x-rays is allowed to strike the face of a crystal at a series of different angles, for each angle the path difference has a characteristic value. Consequently if the beam contains several different wave-lengths, analysis of the mixture is possible because *each component is strongly reflected in a direction different from any of the others.* This is the fundamental principle underlying the construction and use of all instruments for measuring x-ray wave-lengths. It is applied in several different ways, three of which we shall note as being of especial interest to the roentgenologist.

Wave-Length by Rotating Crystal and Ionization Chamber

104. The arrangement as used by Dr. Duane (after Bragg) should be clear from a study of Figure 87. A narrow beam of rays emerging from the slits S_1 and S_2 cut in thick blocks of lead is incident on the face of a crystal C set on the table of an instrument called a spectrometer. By means of a scale attached to this instrument rotations of the crystal through small angles may accurately be measured. A third slit S_3 is so placed that any reflected beam which exists may enter an ionization chamber I placed

* The actual value of the path difference = $2d \sin \Theta$, where d is the distance between successive planes, and Θ is the angle between the direction of the incident beam and the face of the crystal. For a simple proof, see "X-rays and Crystal Structure," p. 17, by Bragg and Bragg.

immediately behind it. For this to be the case the slit S_3 and the chamber must, of course, be placed so that the line O S_3 makes the same angle with the face of the crystal as the incident beam. For each position of the crystal there is, therefore, only one correct position of the second slit and the ionization chamber, both of which accordingly are mounted on an arm by means of which they may be rotated about the central axis through O.

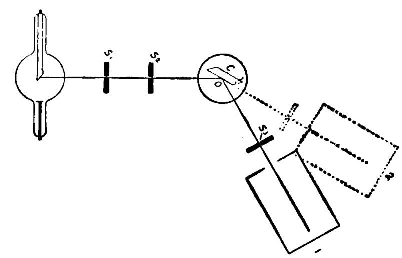

FIG. 87.—Spectrometer with ionization chamber (Duane method).

In actual use the incident beam of x-rays to be analyzed is allowed to strike the face of the crystal at a number of different angles; for each angle the second slit and the ionization chamber is set in the correct position and the ionization current measured. A graph is then made (see Section 107) showing the way in which the ionization current varies with the angle of incidence. From this graph it is not a difficult matter to determine the constituent wave-lengths of a complex beam, since as already noted, the path difference depends on the angle of incidence and is equal to one-length for that component which is strongly reflected.

THE SEEMAN SPECTROGRAPH

105. This instrument, especially designed for radiologists, differs from the type just described chiefly in the use of a photographic plate instead of an ionization chamber. It is small and compact, and for its operation does not require as much experimental skill as for the Bragg spectrometer. The beam to be analyzed enters the instrument by a narrow slit S_1 (Figure 88), is incident on the face of a crystal immediately behind which a second narrow slit S_2

allows any reflected beam which may exist to emerge and finally strike a small photographic plate placed at AB. By means of a clockwork mechanism the portion of the instrument holding the crystal and photo plate is kept in a regular oscillating motion about the second slit as axis. In this way the original beam strikes the crystal behind S_2 at a series of different angles and regular reflection of each component takes place just as in the instrument already described. In this case, however, the "separated" beams fall on a photographic plate and a permanent record is obtained. Fundamentally wave-lengths must be calculated in exactly the same way as by the first method, but with each instrument, the manufacturer provides a scale by means of which wave-lengths may be read off directly from the photographic plate. The instrument is therefore extremely convenient for the practicing radiologist.

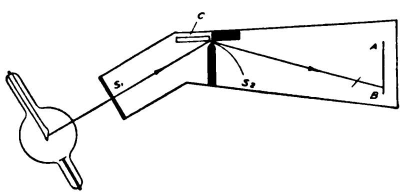

FIG. 88.—Seeman Spectrograph.

THE ROENTGEN SPECTROMETER OF MARCH, STAUNIG AND FRITZ

106. This instrument,[1] which is designed primarily to measure the *shortest* wave-length in a mixture. is even simpler in its operation than the Seeman Spectrograph. By means of two slits S_1 and S_2, Figure 89, a narrow beam of the rays to be analyzed passes *through* a crystal and is incident on a fluorescent screen. If the crystal is rotated it will be seen that reflections may take place internally

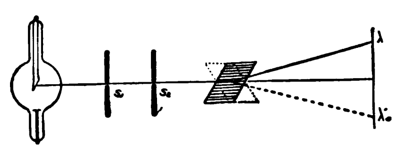

FIG. 89.—Arrangement for spectrometer of March, Staunig and Fritz.

from its parallel planes, somewhat as illustrated in the grossly exaggerated figure. By gradually rotating the crystal, therefore, a position will be reached when the angle of incidence is such that the shortest wave-length in the beam is intensely reflected. The shortest wave-length appears first because it corresponds to the smallest angle between beam and face of the crystal. In this instrument this will be evident by a flashing up of the fluorescent screen at a definite place (λ_0 in Figure 89). Moreover, rotation in the opposite direction will give rise to a reflected beam on the other side of the central one which will give a second fluorescent region at λ_0'. In the type of instrument on the market, therefore, the crystal is rotated in both directions and the position of the two fluorescent regions noted with reference to a scale provided. From this scale the *shortest* wave-length in the beam is simply read off. The importance of a knowledge of the shortest wave-length is discussed below (Section 107).

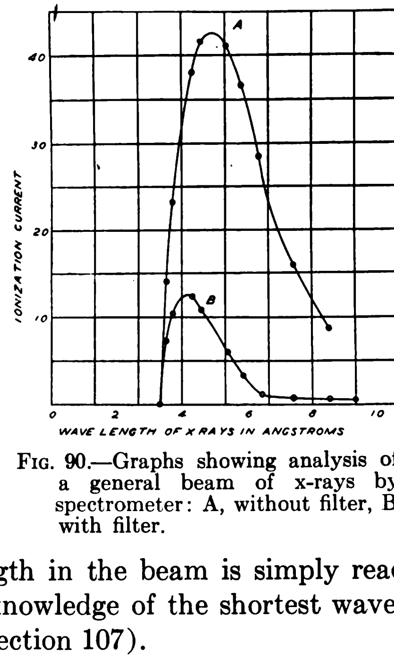

FIG. 90.—Graphs showing analysis of a general beam of x-rays by spectrometer: A, without filter, B with filter.

107. We are now in a position to learn something of the results which have been obtained by means of x-ray spectrometers, as well as by the earlier but less exact absorption methods. (1) The beam of rays leaving the target of any tube even when the voltage operating it is constant, is far from homogeneous. A good example of analysis by means of an x-ray spectrometer (of the Bragg type) is found in Figure 90, where the graphs illustrate some results obtained by Dr. Duane of Harvard University. Curve A

shows the way in which the ionization in the chamber of the spectrometer varies as the chamber is set so that reflected rays enter at different angles, or in other words, it gives the relative intensities of the different wave-lengths into which the composite beam has been analyzed. We see that it represents a beam with wave-lengths ranging from about 0.33 A.U. to about 0.85 A.U. with intensity reaching a maximum at wave-length 0.5 A.U. In this case a constant but not specially high voltage was applied to the tube.

Now it is because of such measurements that we can state, as has already been done, that x-rays used in radiology have wave-lengths ranging from 0.06 A.U. to 0.3 A.U.; and that we can say that soft rays are those with wave-lengths in the neighborhood of 0.3 A.U., while hard rays have wave-lengths of the order of 0.1 A.U. X-ray spectrometry, moreover, has shown that, in general, the shorter the wave-length the more penetrating the rays. To take a concrete example, for λ (symbol for wave-length) $= 0.1$ A.U., the value of D (the half absorption value; see section 82) is equal to about 640 mm. of aluminium; for $\lambda = 0.2$ A. U., D $= 12.2$ mm. of aluminium, while for $\lambda = 0.3$ A. U., D $= 5.7$ mm. of aluminium. Once more then, we emphasize the fact that to give the wave-length or effective wave-length is the most exact way of describing the quality of a beam of x-rays.

(2) The *shortest* wave-length in a mixture depends absolutely and only on the maximum voltage across the tube. This is true whether the potential is constant or variable. If the crest value of the voltage across a tube operated by a transformer is the same as a constant voltage applied to another tube, the shortest wave-lengths emitted by the two tubes are identical. What is even more important, by means of the simple relation given below, the value of the shortest wave-length can be easily calculated.

$$\text{Shortest wave-length} = \frac{12354}{\text{Maximum voltage}} \text{ A.U.}$$

For example, with 80,000 volts (maximum or crest) across a tube, the shortest wave-length $= \frac{12354}{80000}$ or .15 A.U. With 250,000 volts (deep therapy), the shortest wave-length emitted is $\frac{12354}{250000}$ or 0.049 A.U.

While the shortest wave-length is by no means the most intense (see Figure 90 again), a knowledge of its value gives a fair indication of the quality of a beam of rays. In many cases, according to Kaye, the wave-length of the greatest intensity is roughly 1.2-1.3 times that of the shortest component.

The X-Ray Spectrometer as High Tension Voltmeter

The above relation may evidently be written, Maximum voltage $= \frac{12354}{\text{shortest wave-length}}$. If, therefore, the wave-length can be read off from a scale provided in an instrument (as is the case in the Seeman Spectrograph), we are thus provided with a new and an accurate means of measuring the highest voltage. Indeed, the accuracy of this method exceeds that of any of those discussed in Chapter II.

(3) The rays leaving the target of an x-ray tube may consist of two kinds, (a) a general or independent or "white" radiation, (b) a characteristic radiation. An example of general radiation has already been given in Figure 90, where, as we have already noted, we have to do with a whole *range* of wave-lengths running *continuously* from a lower to a higher limit. In this case the magnitude of the wave-lengths emitted are independent of the material of which the target is composed.

On the other hand, characteristic radiation consists of a certain few *isolated* wave-lengths whose magnitude depends on the material of the target. A very exact analogy is found

in the case of ordinary "visible" light. If the light from a carbon arc is observed through a spectroscope, or, having passed through a prism, is allowed to fall on a screen, one sees a continuous spectrum having all colors ranging from red to violet. If, while the carbon arc is still burning, it is fed with a small quantity of a salt of some element, such as barium for example, one sees superimposed on the continuous spectrum certain isolated narrow colored bands, spectral lines, as we call them. Should the nature of the salt be changed the same phenomenon would be observed, with however, the colored lines in different positions. In other words, the number and the position of these spectral lines depend on the substance put in the arc and are characteristic of it. To return again to x-rays, the continuous spectrum corresponds to the general radiation, while the isolated lines are exactly analogous to the characteristic radiations.

Independent or General Radiation

108. It is necessary, now, to say something about each of these types of radiation. Figure 90 is fairly typical of the distribution of wave-lengths in the general beam. Regarding the manner in which they range from the shortest wave-length through one of maximum intensity to a limit on the long wave side, sufficient has already been said. One further point, however, may be noted. The *total* intensity of the beam of general rays has been measured under different conditions and it has been shown to depend on (a) The current through the tube. Double the current, the intensity is doubled; that is, the intensity is directly proportional to the current. (b) The voltage across the tube. Double the voltage, the intensity is quadrupled; that is, the intensity depends on the *square* of the voltage. (c) The atomic number of the material of which the target is made. The higher the atomic number, the more intense

the beam. For example, under the same conditions of current and voltage, a tube with tungsten target (atomic number 74) emits a beam whose intensity is less than a tube with platinum target (atomic number 78) in the ratio,

$$\frac{74 \times 74}{78 \times 78}.$$

It follows, therefore, that when increase in intensity is desired, something is gained by using targets of as high atomic weights as possible.

Characteristic Rays

109. (1) A photograph taken with a Seeman spectrograph or any similar instrument, reveals (a) a continuous blackening across the plate ending at the shortest wave-length of the general radiation, and (b) *if the voltage is high enough,* certain isolated black lines superimposed on the continuous background. These lines are due to the characteristic radiations emitted by the target and, as

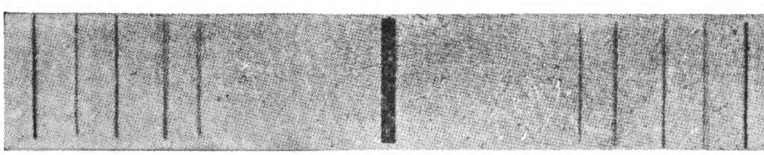

Fig. 91.—Characteristic x-ray spectral lines (Mueller).

already noted, have definite wave-lengths which may be accurately measured. Figure 91, a reproduction of a photograph taken by Mueller,[2] gives a good example of the photographic appearance of characteristic x-ray spectral lines. In this photograph the same lines appear on each side of a central band, because the arrangement was not unlike that of March, Staunig, and Fritz (Section 106).

Figure 91A shows a series of spectrograms taken at different voltages, in most of which both general and characteristic radiations may be seen. In all but Number 1,

one may see the continuous blackening due to the general radiation, together with the sharply defined limit on the

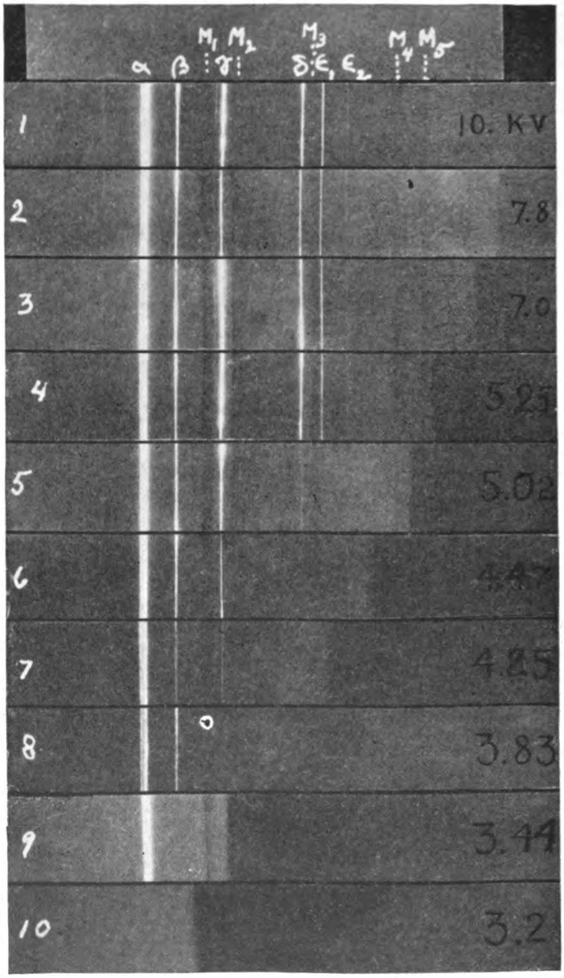

FIG. 91A.—Spectrograms showing short wave-length limit at different voltages, as well as characteristic lines (Ross).

short wave-length side. Moreover, as the voltage is gradually reduced, from 7.8 kilovolts in Number 2 to 3.2 kilovolts in Number 10, the way in which this limit is

shifted to the long wave-length side (in accordance with the relation of Section 107) is clearly shown. These same photographs provide excellent examples of the appearance of characteristic lines, which may be seen in all but number 10. In this case the voltage was not high enough to

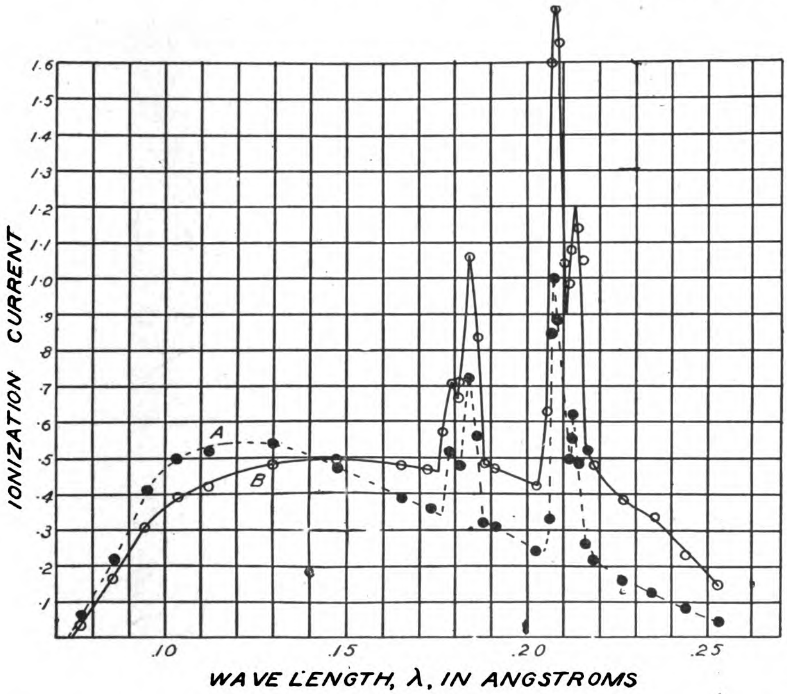

FIG. 92.—Analysis of a beam of x-rays, with characteristic peaks: A, with filter 1 mm. copper; B, with filter 12 mm. of aluminium.

excite them. (See 2 below.) The spectrograms of Figure 91A were taken by Mr. P. A. Ross of Stanford University, through whose kindness it has been possible to reproduce them in this book.

Experiments with ionization chambers and the Bragg type of spectrometer show the same phenomena. Figure 92 (a rough copy of one due to Dr. Duane) shows the type of curve obtained when a much higher voltage is across

the tube than was the case in Figure 90. The high peaks in the curve of Figure 92 are obviously an indication of the fact that in the beam there are certain *isolated* wave-lengths of marked intensity. These are the characteristic radiations of tungsten. Now should a tube with another target be used, there would be peaks corresponding to different wave-lengths, just as in the photographic method, the narrow spectral lines would occur at different places on the plate. With tungsten, characteristic radiations are observed at wave-lengths 0.179, 0.184, 0.209, .2134 A.U. (Henceforth we shall omit the unit, all wave-lengths being given in Angstroms); change to uranium, however, and peaks occur at 0.111, 0.126, and 0.131.

(2) Characteristic rays do not appear unless the voltage across a tube is sufficiently high. In the case of tungsten, for example, potentials of the order 80,000-100,000 volts are necessary, while in the case of uranium, characteristic rays do not appear until nearly 115,000 volts have been used. This has an important practical application. Because of the possible presence of characteristic rays in a beam it follows that its mean quality cannot be fixed *solely* by even an accurate knowledge of the crest voltage. It depends also on the material of which the target is made. Once more then, we are made to realize that an exact knowledge of the electrical conditions under which a tube is operating is not enough for an exact knowledge of the quality of the beam leaving the tube. When using 80,000-100,000 volts, tungsten would be a better target to use than uranium, because this voltage is not sufficient to bring out the characteristic rays of the latter.

If the voltage necessary to bring out a set of characteristic lines of one element is known, that necessary to excite those of another element may readily be found from the fact that the required voltage is proportional to the square of the atomic number. Platinum, for example, ($N = 78$)

would require a voltage higher than tungsten in the ratio $\frac{78 \times 78}{74 \times 74}$, while uranium (N = 92) requires a much higher potential than either of these. On the other hand, the higher voltage excites shorter wave-lengths in the case of the elements of higher atomic number. This is clearly shown in Table XVI, where corresponding prominent characteristic wave-lengths of four elements are given.

TABLE XVI

	Copper	*Silver*	*Tungsten*	*Uranium*
Wave-length	1.54	.56	.21	.15
Atomic number	29	47	74	92

At one time it was thought that it might be desirable to construct tubes with uranium targets and so to make use (in deep therapy) of the characteristic rays of this element, with a minimum wave-length of 0.105 as compared with .179 for tungsten. Now, however, the aim is rather to build tubes which will stand higher and higher voltages, and so to utilize the short waves of the general beam. "A voltage as high as 3,000,000 could probably be produced, and, if a suitable tube could be developed, it would probably be possible to operate it from such a source—in oil, not in air, as the spark length would be close to thirty feet." (Coolidge.) Applying the relation given above, this voltage would give rise to a minimum wave-length of $\frac{12354}{3,000,000}$ or 0.004 A.U. In the meantime most roentgenologists will probably find that there is ample for them to do with a 250,000 volt machine.

(3) An analysis of *all* the characteristic wave-lengths emitted by a single element shows that they may be divided into groups. These may be explained by taking tungsten as a typical example.

TABLE XVII

Group 1	*Group 2*	*Group 3*
K	L	M
.213	1.67	6.97
.208	1.48	6.75
.184	1.47	6.09
.179	1.42	...
...	1.30	...
...	1.28	...
...	1.26	...
...	1.26	...
...	1.20	...
...	1.09	...
...	1.06	...
...	1.03	...

A glance at Table XVII will show the existence of the three sets of wave-lengths which are universally designated by the letters K, L, and M. It will be seen from the numerical values that the L and M series have wave-lengths too long (that is, are too soft) to be of any use in radiology. They are absorbed by the walls of an ordinary x-ray tube, and have no practical interest for the radiologist. The K series, however, is important because in the case of all elements of high atomic number, all the wave-lengths which it comprises are within the useful range in radiology.

To sum up, then, the beam of rays leaving an x-ray tube comprises a whole range of wave-lengths whose shortest magnitude may readily be found but whose general character may be complicated by the presence of certain rays characteristic of the metal of the target. By means of an x-ray spectrometer, however, it is possible to make an accurate analysis of the mixture *in terms of universal standards*. There need, therefore, be no confusion when different radiologists report the character of radiations used.

110. There is another matter, however, which is not quite so simple. For effective progress in the use of x-rays for treatment it is desirable to utilize beams as homogeneous

in character (that is, as monochromatic, to borrow a term from light) as possible. Obviously, one wave-length may be more *effective in treatment than another.**

Can this homogeneity be obtained? The ideal way consists in the use of a spectrometer for isolating a small range of wave-lengths. Practically this is not so simple a matter as the mere analysis of the beam by the methods described above, and for radiologists the less accurate but extremely useful method of filtration is the only method. In this connection we may state here that homogeneous beams of greatest purity are obtained by operating a tube on a voltage somewhat greater than that necessary to bring out the characteristic rays of the target together with suitable filter. But even in the case of an element with such a high atomic number as uranium, the resulting wave-lengths are not short enough for deep therapy, and in practice, as already noted, the radiologist uses a much higher voltage and the resulting short wave-lengths of the general beam.

Filtration and Wave-Length

111. The general principles of filtration have already been discussed (Section 84). We are now, however, in a position to examine this question in the light of the accurate wave-length analysis which the x-ray spectrometer has made possible. Some of the important results shall be noted.

(1) Rays which, according to the absorption method (Section 84) have been made homogeneous by filtration, are by no means monochromatic; that is, such filtered rays also consist of a mixture of many wave-lengths. Curve B (Figure 90), for example, shows the effect of a filter of aluminium on the beam for which curve A gives the un-

* In this connection see recent paper by Russ on the effect of x-rays of different wave-lengths upon animal tissue. *Proc. Roy. Soc.* B, 95, 131, 1923.

filtered analysis. Generally speaking, however, the filter absorbs long waves (soft rays) more than those of short wave-length, and the beam is thereby made on the average both more penetrating and more homogeneous.

(2) Beyond a certain minimum value increased thickness, while it reduces the intensity of the beam, gives rise to but little gain in homogeneity.

(3) The shortest wave-length is not affected by the filter, as is clearly shown in Figure 90. The relation connecting the value of the shortest wave-length with the applied voltage applies equally to filtered and unfiltered rays.

(4) Care must be exercised in the choice of a suitable metal for filter. We can readily obtain sheets of iron, copper, lead, aluminium, zinc and tin. Are all equally suitable? The answer to this question is found in some very important measurements on what are called critical absorption wave-lengths of the elements, the values of which for the above common metals are given in Table XVIII.

TABLE XVIII

Critical Absorption of Wave-Lengths	
Aluminium	7.95 A.U.
Iron	1.74
Copper	1.38
Zinc	1.30
Tin	0.42
Lead	0.14
Silver	0.485

In so-called *normal* filtration, which we have been discussing (and this is the kind of chief interest to the radiologist), a filter is effective because it absorbs the long soft rays more than short harder ones. But this is not always the case, because for every element there is what is called a *critical absorption wave-length.* This simply means that, in the neighborhood of this critical wave-length, waves

just shorter in length are abnormally absorbed,—much more, in fact, than those just longer. It is not until waves considerably shorter have been reached that the substance once more becomes as transparent as it had been for waves on the long side of the critical absorption value. To take a concrete case, lead absorbs wave-lengths just less than 0.14 A.U. (see Table XVIII) much more than those longer than this critical value. Now wave-lengths shorter than 0.14 are the highly penetrating kind which are utilized in deep therapy. It follows, therefore, that a filter of lead would be practically useless for normal purposes. There is, however, no serious objection to any of the other metals given in Table XVIII because all the wave-lengths used in radiology are so very much shorter than the critical absorption wave-lengths. In actual practice filters of aluminium, copper, zinc, and brass are in general use.

(5) On the other hand, even in the case of metals all of which are suitable for normal filtration, one may be better than another. For example, Duane has shown that 1 mm. of copper is more effective than 12 mm. of aluminium in absorbing waves longer than 0.141 A.U. but less effective for waves shorter than this value. That this is the case will be evident from a comparison of the two curves of Figure 92. Curve A gives the analysis of a beam with a filter of 1 mm. of copper, curve B with a filter of 12 mm. of aluminium. It will be noted that at wave-length 0.141 the two curves cross one another. It follows, therefore, that if it is desired to have a beam with an excess of the shortest waves possible, copper is a better filter to use than aluminium.

The Effective Wave-Length

(6) It is hoped that it is now clearly evident that the only exact way of describing the character of a beam is by giving the relative intensities of its component wave-lengths. To do so some type of x-ray spectrometer is nec-

essary, and such an instrument may not be in the possession of every radiologist. Such a man has always resource to the less exact penetrometers already described, but thanks to the labors of Dr. Duane, it is possible for him, even

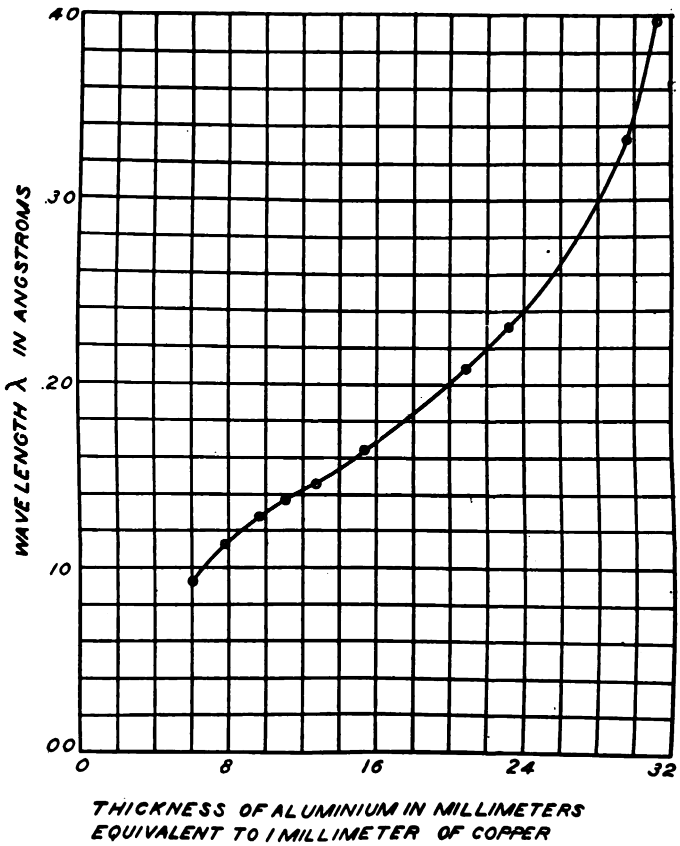

FIG. 93.—Standard graph after Duane by means of which the effective wave-length may be found.

without a spectrometer, to describe the quality of a beam in terms of its *effective wave-length.* By this is meant the wave-length whose coefficient of absorption is the same as that for the whole beam. "It is this effective wave-length which is important in many cases—for the physiological

effect of the rays appears to depend upon the amount of radiation absorbed." (Duane.)[3]

112. To find the effective wave-length of a beam use must be made of the standard graph made from measurements taken by Dr. Duane and reproduced in Figure 93. (By consulting the original paper to which reference is made at the end of this chapter a second method along similar lines will be found.) The method depends on the fact already noted, that the relative absorbing power of copper and of aluminium is not the same for all wave-lengths. For wave-lengths of the order of 0.1 A.U., for example, 7 or 8 mm. of aluminium are required to absorb as much as 1 mm. of copper, while for wave-lengths in the neighborhood of 0.2 A.U. it takes about 20 mm. of aluminium. *For each wave-length, therefore, there is a definite thickness of aluminium which absorbs to the same extent as 1 mm. of copper.* Now such equivalent thicknesses of aluminium have been determined by Dr. Duane for a whole range of wave-lengths and the graph of Figure 93 gives the result. To use this graph for determining the effective wave-length of a beam, it is necessary first of all to determine (by means of an electroscope or by an examination of the blackening of a photographic plate), how much the beam is reduced in intensity by 1 mm. of copper (see Sections 136, 142). Next the copper plate is replaced by increasing thicknesses of aluminium until a thickness is obtained such that the reduction in intensity of the beam is the same as for copper. Suppose it were 16 mm., then from the graph of Figure 93 one finds the wave-length which has the same absorption to be about 0.17 A.U. This then, would be the effective wave-length of the beam.

In this connection one further point may be noted. Any thickness of copper may be used, provided the operator determines the *number of times* the aluminium thickness is greater than that of the copper. For example, in the case just considered a copper filter of ½ mm. might be

used, in which case the equivalent thickness of aluminium would be 8 mm., that is, again sixteen times that of copper. The exact thickness of copper to be used would naturally depend on how penetrating a beam was utilized.

Focal Spot and Its Relation to Wave-Length

113. In earlier pages reference has been made to differences in the size of the focal spots on the targets of tubes. Before concluding this chapter, it is desirable to look at this question in the light of our knowledge that x-rays are short ether waves. Since this is the case, in radiography and fluoroscopy, the radiologist is dealing with shadow pictures, the details of which should be as clearly defined as possible. To obtain good detail, sharp shadows are

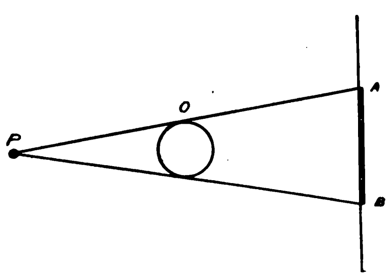

Fig. 94.—A small source of light casts a sharp shadow.

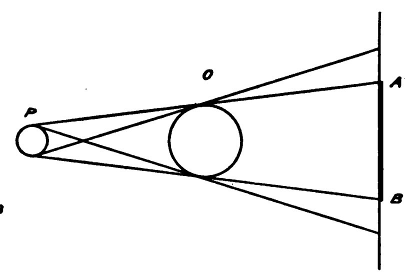

Fig. 95.—A source of light which does not cast a sharp shadow.

necessary and these can only be obtained by having a small source of rays, that is, a fairly fine focal spot. The case is exactly analogous to the shadow patterns of obstacles placed in the path of light rays. A small source of light such as P, Figure 94 (an uncovered arc lamp, for example), casts a sharp shadow of an object O on a screen. If, however, the source of light is comparable in size with the object, as shown in Figure 95, the portion of the shadow AB will be completely dark, whereas around it will be a region which receives light from some parts of

the source, but which is cut off from other parts. The shadow is not sharp. In radiography it is exactly the same, and for good pictures it is necessary to have as fine a focus as the energy conditions will allow. However, care should be exercised that rays generated from parts of the tube other than the focal spot (as sometimes happens, since wherever electrons hit, x-rays originate) are not allowed to fall on the body to be examined.

On the other hand, in treatment, it is a question solely of the absorption of radiation and there is no need whatever to have a fine focus. Indeed, as in treatment a tube is generally operated continuously for some time, it is highly desirable that such be not the case.

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2. Mueller, *Phil. Mag.,* 42, 419, 1921.
3. Duane, *Amer. Jour. of Roent.,* IX, 167, 1922.

CHAPTER X

SECONDARY X-RAYS

114. We may introduce this important subject by referring to an interesting experiment performed by Friedrich and Kroenig. Readings of the intensity of a beam of x-rays were taken with a filter, (1) halfway between the target of the tube and an ionization chamber, (2) directly in front of the ionization chamber. Conditions in the two cases were otherwise identical. In the case of a copper filter 1 mm. in thickness, it was found that the intensity of the beam was 16 per cent greater when the filter was in the second position. What is the explanation? It may perhaps best be given by reference to another experiment.

Suppose an electroscope is completely shielded from a beam of x-rays emerging from a hole, S (Figure 96), cut in a sheet of lead so thick that normally no ionization is indicated by the instrument. Suppose, further, that a piece of any substance preferably of low density such as a thin layer of aluminium R, is placed in the path of the direct beam as shown in the illustration. It is then found that the presence of the aluminium causes an ionization current to be indicated by the electroscope. This is the case with the instrument anywhere near the aluminium, although always out of the path of the direct beam of x-rays. The explanation is found in the fact that when x-rays fall on matter (at least some kinds of matter), what are called *secondary x-rays* are emitted in all directions. In the experiment of Friedrich and Kroenig to which reference has been made, more of these secondary rays could enter the ionization chamber when the copper filter was

immediately before it than when at some distance away, hence the 16 per cent difference in the intensity of the beam as recorded by the measuring instrument. As secondary rays are of great practical importance to the radiolo-

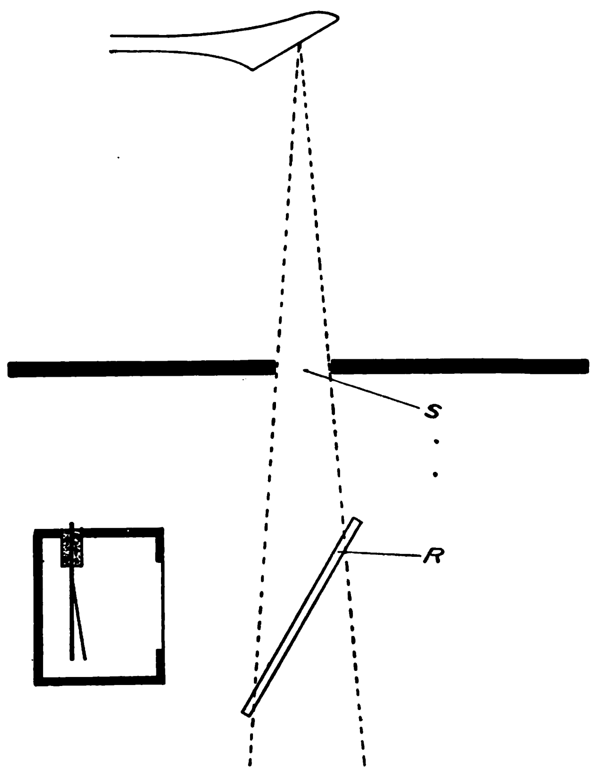

FIG. 96.—Experimental arrangement to show existence of secondary x-rays.

gist, it is necessary now to consider this question somewhat in detail.

115. As the result of the work of many investigators it is known that when x-rays pass through matter a threefold radiation may be emitted—(1) x-rays of the same type as the primary beam, known as *scattered rays;* *

* There is some experimental evidence that scattered rays may be slightly softer than the primary beam.

(2) x-rays characteristic of the matter "excited" by the primary beam, known as *characteristic "fluorescent" rays;* (3) an emission of electrons which is always associated with the beam of characteristic fluorescent rays, and is called a *corpuscular emission.* Secondary x-rays include the first two classes. Once again, useful analogies are found in the case of ordinary light. If there is much dust in a darkened room it is an easy matter to "see" a beam of light from an arc lantern. If a red glass is placed in front of the arc, the beam appears red because red light is reflected by the dust particles in all directions. Now the phenomenon of scattering of x-rays, while not exactly the same, is not unlike this scattering of light in all directions by dust particles. It consists in a re-emission in all directions of rays of the same kind as the primary beam.

Again if certain substances are placed in the path of the beam from an arc light, or in direct sunlight, they are seen to fluoresce with a brilliant and characteristic color. Uranium glass, for example, emits a brilliant greenish light in this way; a solution of sulphate of quinine in sulphuric acid shows a characteristic and beautiful blue, and so on for many other substances. This fluorescent light, therefore, is characteristic of the substance and is caused by the excitation by the primary beam of light falling in it. Characteristic fluorescent x-rays are closely analogous. They are characteristic of the substance and result from its stimulation by a primary beam.

Even the corpuscular emission is an example of what is known as a photo-electric emission of electrons which takes place when light falls on substances. If, for example, ultra-violet light is allowed to fall on a zinc plate joined to a negatively charged electroscope, it is found that the electroscope soon loses its charge. The stimulus of the light causes an emission of electrons from the zinc plate. So in x-radiation, when a beam falls on matter, there may be

an emission of electrons which, however, is always accompanied by the characteristic fluorescent radiation.

We shall next look at some of the laws relating to secondary rays, and then pass on to consider their importance in radiology.

Scattered Rays

116. (1) As already noted, these are of the same quality as the primary beam. (2) Scattering takes place in all directions about the radiator but the intensity has its maximum value in the same direction as the primary beam. (3) *Scattering is most pronounced with substances of low atomic weight and therefore is of great importance in human tissue which contains such an excess of light elements.* (4) "With the copper group of elements, the scattered radiation is so small in amount that it is, for most purposes, negligible." (Kaye.)

Characteristic Fluorescent Rays

117. (1) These are identical with the characteristic rays which have already been discussed. (Section 109.) The difference between secondary characteristic or fluorescent rays and those leaving the target of a tube lies solely in their mode of generation. Fluorescent rays are generated as a result not of the impact of electrons on a target but of the stimulus of an exciting, primary beam of x-rays. X-rays may excite x-rays when falling on matter.

(2) To excite fluorescent rays the primary beam must in general be harder, that is, of shorter mean wave-length. On the other hand, the quality of the characteristic beam depends solely on the material of which the radiator is composed.

(3) The intensity of the fluorescent beam is the same in all directions about the radiator.

(4) "Characteristic radiations from materials of very

low or very high atomic weight are either very soft or absent altogether; and so carbon, paraffin wax, aluminium, lead and metals of the platinum group are ordinarily to be preferred to metals of the chromium-zinc group, which possess pronounced characteristic radiations." (Kaye.)

It should be evident, therefore, that the radiologist is chiefly interested in scattered x-rays, the effects of which may be almost as important as those of the primary beam. Two outstanding examples of their importance will be discussed, one relating to radiography, the other to deep therapy.

Scattered Rays and Radiography

118. The aim of the radiographer is to obtain a shadow picture showing good contrast and definition. That scattered rays may, in some cases, lessen the sharpness of the picture to such an extent as to make it of little use should be evident from an inspection of Figure 97. In this illustration a, b and c represent the shadows of three small

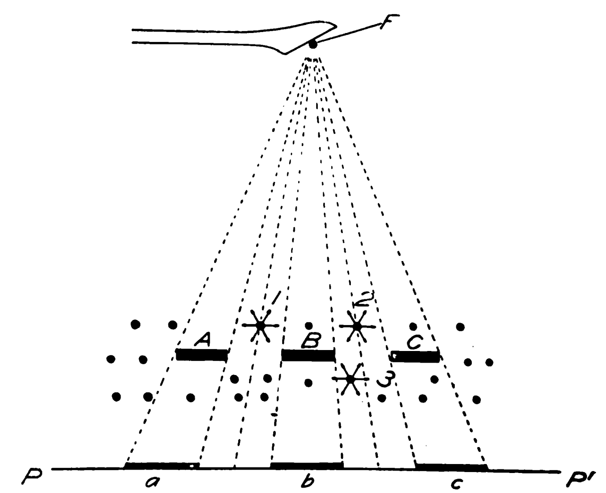

Fig. 97.—Shadows of objects A, B and C are not sharp because of effect of secondary x-rays.

obstacles, A, B and C, on a photographic plate or film. If scattered rays were of no importance and the focal spot at F were fairly small, such shadows would ordinarily be sharp and the plate would show marked differences in density between the regions a, b, and c and their surroundings. (Section 113.) Suppose, however, the objects A, B and C are surrounded by other particles of matter (as indicated by the small dots) which scatter x-rays in

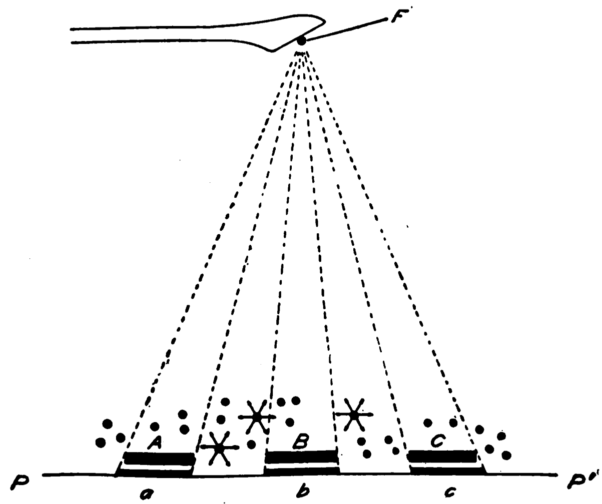

FIG. 98.—Shadows of objects A, B and C are sharp when objects are close to photographic plate.

all directions. In that case sharp shadows would only be possible when the objects A, B, C were placed near the plate or film, somewhat as illustrated in Figure 98. If the objects are not near the film, sharp shadows will no longer be possible, for two reasons. In the first place, the scattered rays from each particle such as 1 and 2, will cast their own shadows, and for each particle the shadow due to this cause will occupy a different position. Again, scattered rays from many of the particles can pass under the objects and in this way affect the photographic plate in the region which the object shields from primary rays.

For these reasons a good radiograph under such conditions would be impossible. Now whenever an operator wishes to make a radiograph of a thick portion of the body, he is up against this difficulty. Certain parts cannot be brought near the plate and scattering of x-rays makes it impossible to obtain good results. Can the difficulty be overcome in any way?

There are two ways in which the desired improvement in contrast may be obtained, (1) by diaphragming, (2) by the use of the Potter-Bucky Diaphragm.

Diaphragms and Secondary Rays

119. Diaphragming consists in limiting the aperture of the primary beam to the smallest possible extent. In

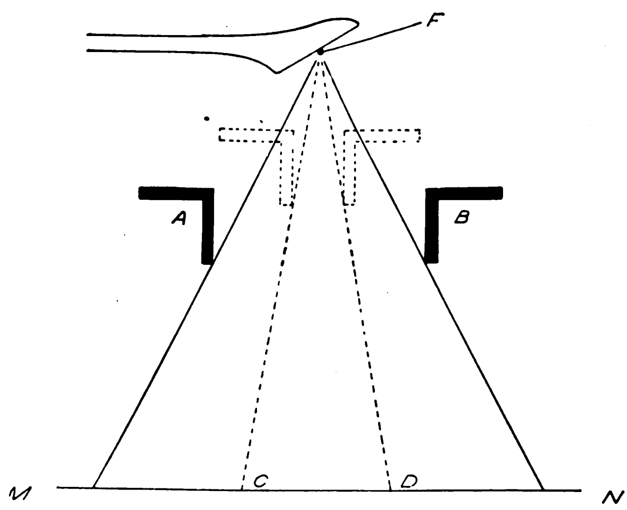

Fig. 99.—Effect of Diaphragms on cone of rays.

Figure 99, for example, AB represents a diaphragm which limits the area of the beam on the plate to M N, whereas had a diaphragm been used of the size indicated by the dotted lines, the area would have been limited to C D.

If now it is possible to diaphragm sufficiently when radiographing a thick body, considerable improvement in the contrast can be obtained. This may best be shown by giving some experimental results of Wilsey, of the Eastman Kodak Co., who has made an extended study of the effects of scattered rays in radiography.[1]

Wilsey by a simple experimental arrangement was able to compare the photographic intensity of the primary or focal beam with that of the scattered.* Using an aperture which gave a picture on the plate 20 inches in diameter, and a layer of water 6 inches thick as the scattering material, he found scattered radiation to be 4.9 times that of the focal beam. By diaphragming until the picture was 8 inches in diameter scattered radiation was reduced to 4 times the focal, while if the picture were made 4 inches in diameter, the ratio was reduced to 2. In other words, if one could conveniently use a picture 4 inches in diameter, the effect of scattered rays is cut down considerably, but with a scattering layer 6 inches thick the effect of scattered rays is still twice that of the direct rays from the focal spot. While some improvement, therefore, is obtained by cutting down the aperture of the beam, the method is limited in its application and at the best not very efficient.

The Potter-Bucky Diaphragm

120. In the Potter-Bucky Diaphragm, however, the radiographer is supplied with an arrangement which very considerably reduces the effect of scattered rays when thick portions of the body are being photographed. The underlying principle, as first suggested by Bucky, is simple. Suppose (Figure 100) a grid of lead strips, separated by narrow slots, is placed between the object to be radiographed and the photographic plate. If the lead strips are placed

* Under "scattered" is also included the radiation which might be present due to rays originating at places other than the focal spot.

so that they lie lengthwise along a curve somewhat as shown in the figure, it should be evident that the only rays which can get through the slots and so strike the photo plate are those in the direction of the focal beam. Secondary rays in other directions are cut off by the lead strips, as is clearly shown in the figure in the case of a few rays from particles 1, 2 and 3. Sharp shadows of objects

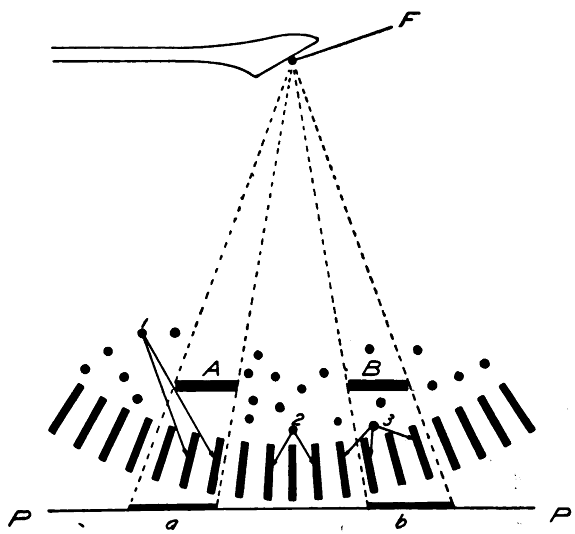

FIG. 100.—Shadows of objects A and B are cast only by rays in direction of primary beam.

such as A and B, therefore, are cast. With a stationary grid of the kind described, however, such radiographs would be of little use, because the shadows of the lead strips themselves would be superimposed on the picture.

In the Potter-Bucky diaphragm this difficulty is overcome by adopting the simple device suggested by Dr. Potter, of keeping the grid in steady motion throughout an exposure. By this means, since each portion of the plate is covered for the same length of time by each lead strip, the effect of grid shadows is eliminated. With such an

arrangement excellent radiographs may be made of the thick portions of the body. The grid moves along a curved track and is thus always in the position to allow the passage of primary rays, while immediately above the grid a thin curved sheet of metal supports the patient. Details of the mechanism controlling its movement will be found in the original papers.[2] Some idea of its appearance will be gathered from Figure 99A.

121. The device is so useful and important that certain further points should be noted. (1) The grid is equally efficient over the whole area covered. With a flat plate,

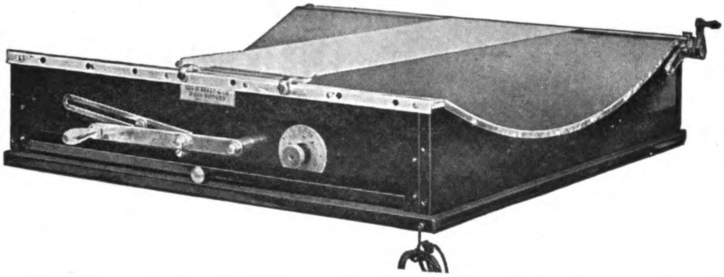

FIG. 99A.—The Potter Bucky Diaphragm (Geo. W. Brady & Co.).

however, the efficiency at the edges is not as high as at the center, where the plate is much closer to the grid. This difficulty may be obviated by using a curved cassette for holding a film with all parts close to the grid, an idea originally due to Van Allen.[3]

(2) The time of exposure is considerably increased, some four or five times. This should be evident when it is remembered that with a 6″ layer of scattering material and a large aperture, the intensity of scattered radiation is nearly five times that of the focal beam. As almost all of the scattered radiation is removed, it is the focal radiation alone which is affecting the photographic film, and increased exposures are therefore necessary.

(3) The effectiveness of the diaphragm depends not on

the actual depth of the slots, but on the ratio of their width to their depth. To give an actual example from Wilsey's measurements, if the slot width equals $1/5$ slot depth, from 85 to 90 per cent of scattered radiation is removed, with a 6 inch layer of water as scattering material. If the slot width is reduced to $1/10$ slot depth, the efficiency increases to 93 per cent.

(4) For reasons already noted, this diaphragm is of use only when thick portions of the body are being radiographed, and even then its efficiency is not high unless the distance from patient to film is kept very small. "When the distance between scattering material and film was as large as *one inch,* the smallest slit ratio tried (about $1/22$), failed to give as good definition as was obtained without the use of any diaphragm. . . . The problem in grid design, then, is to make the grid as thin and fine-meshed as possible." (Wilsey.) As Wilsey has made an extended investigation regarding the most suitable dimensions, it may be of interest to readers to give some of his actual results in connection with a highly efficient grid. "The slit depth is 0.16 of an inch, the slit width 0.05 of an inch, making the slit ratio practically one-third. The lead strips are 0.010 of an inch thick; the filling material consists of strips of celluloid. The whole grid is supported in a substantial frame with a curved aluminium floor 0.02 of an inch thick. The top cover of the diaphragm is of aluminium one thirty-second of an inch thick and the top of the curved cassette is of the same thickness." With such dimensions it was found that "when the diaphragm cover was supporting a weight or was under compression the distance between it and the film was about five-sixteenths of an inch."

Before the effect of scattered rays in deep therapy can be considered it is necessary to discuss the whole question of treatment and dosage. In the next chapter a detailed consideration of this important question will be given.

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2. Potter, *Amer. Jour. of Roent.,* VII, 292, 1920; Lindsay, *Amer. Jour. of Roent.,* IX, 67, 1922.
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CHAPTER XI

DOSAGE

122. For the intelligent use of a beam of x-rays for any purpose two things must be known, (1) its quality, (2) its intensity. In preceding chapters we have sought to show how the quality of x-rays may be accurately and universally defined by giving the constituent wave-lengths or the effective wave-length of the beam. So far however nothing has been said about the *intensity* of the radiation. The distinction between the two quantities, while simple, is so important that it is worth while noting an optical illustration. Suppose a red glass is held in the path of the beam of light emerging from a projection lantern and falling on a screen. If the light inside the lantern is made brighter (as can readily be done in the case of an electric arc by increasing the current), the red spot also becomes brighter. The light falling on the screen is still red, that is, its quality is unchanged but its intensity has been increased.

Again in sound, a tuning fork may be struck very lightly so that it is difficult to hear the emitted note, or it may be struck violently and heard at a considerable distance. In both cases the quality of the emitted note is the same; in the latter case, however, the intensity is greatly increased.

So in x-rays, we might operate a Coolidge tube always at constant voltage, but in one case with low milliamperage, in a second case, high. The effective wave-lengths in the two cases would differ but little; in the second case, however, the intensity would be greater than in the former.

Now in radiography, and in treatment especially, an

exact knowledge of the intensity as well as of the quality is necessary. In radiography, after rays of proper penetration (wave-length) have been chosen, the time of exposure must be adjusted to suit the intensity of the beam. In treatment the correct "dose" is only possible when the intensity of the beam is known. It is highly important, therefore, to have some means of comparing the intensities of two beams, and of ascertaining how the intensity of a beam varies with the conditions of excitation.

123. Before discussing direct means of measuring the intensity of a beam, we may note a few preliminary points. First of all let us define exactly what is meant by the term. It is agreed to measure the intensity of a beam of

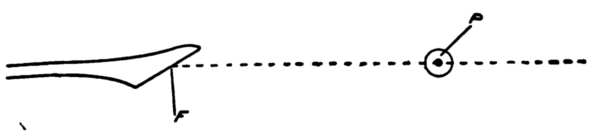

FIG. 101.—Intensity of Radiation at P is measured by the quantity of radiant energy passing through an area of 1 sq. cm. at P, at right angles to line FP.

x-rays at a given region (just like light radiation) by the quantity of radiant energy which each second passes through an area of one square centimeter placed at right angles to the direction of the beam at the region in question. In Figure 101, for example, the intensity at P is measured by the radiant energy which each second traverses an area of 1 sq. cm. (represented by the circle) placed at right angles to the line joining P to F, the focal spot.

(1) From this definition it should not be difficult to see that *the intensity of a beam falls off with increasing distance according to the inverse square law.* In other words, at double the distance from the source, the intensity becomes not one-half but one-quarter, ($1/2^2$); at three times the distance, the intensity becomes one ninth, ($1/3^2$). The reason should be clear from a glance at Figure 102. Suppose ABCD is an area 1 cm. $\times$ 1 cm. at a certain distance

from F, the focal spot on a target, while A′B′C′D′ is exactly twice as far away. Since the lengths A′B′ and C′D′ will each be twice the lengths of AB and CD, the *area* A′B′C′D′ will be 2 × 2 or 4 sq. cm. It follows that the same amount of energy each second passes through A′B′C′D′ or 4 sq. cm. as passes through ABCD or 1 sq. cm. In other words, double the distance, the intensity is reduced to one quarter, or, in general, the intensity falls off inversely as the square of the distance. This law has amply been confirmed by direct experiment.

(2) For general x-rays (Section 108), it has been shown that the intensity of the beam increases, (a) with the

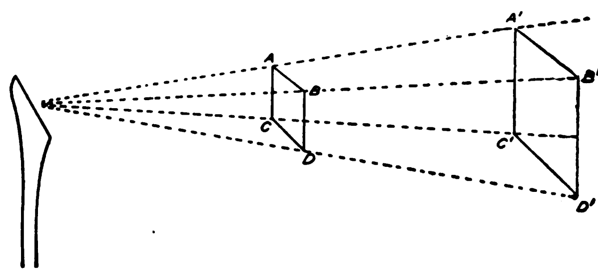

FIG. 102.—If A′B′ = 2 AB, the area A′B′C′D′ is four times area ABCD.

current through the tube: double the milliamperage, the intensity is doubled; (b) with the voltage across the tube: double the voltage, the intensity is increased *fourfold;* (c) the atomic number N of the target: the higher N the greater the intensity. Putting these laws in symbols, we may write, the intensity of a beam of general x-rays is proportional to $N\,i\,V^2$, where i = tube current, N = atomic number, and V = potential difference between the two sides of the tube.

In general, therefore, an operator with a certain outfit, has a right to assume (if he is using general x-rays, which at high voltages would be largely the case) that if he doubles his tube current, the intensity at any point is doubled; if however, he doubles the tube voltage, the

intensity is increased *fourfold.* Moreover, if he keeps current and voltage constant and changes the target distance, he knows that the intensity falls off according to the inverse square law. In general, therefore, the intensity of a beam at a given region is proportional to the number obtained when observed values are substituted in the expression

$$\frac{(\text{milliamperage}) \times (\text{voltage})^2}{(\text{target distance})^2}.$$

Suppose, for example, we wish to compare the intensities at two points A and B, with the following conditions:

Point A—Target Distance = 40 cm.
Tube voltage = 160,000 volts = 160 kilovolts.
Tube current = 10 ma.

Point B—Target Distance = 50 cm.
Tube voltage = 125,000 volts = 125 kilovolts.
Tube current = 8 ma.

Then, filling in proper values in the above expression, we see at once that

$$\frac{\text{Intensity at A}}{\text{Intensity at B}} = \frac{\dfrac{10 \times (160)^2}{40^2}}{\dfrac{8 \times (125)^2}{50^2}} = \frac{160}{50} = 3.2.$$

124. In treatment, therefore, it is possible for a radiologist to alter the intensity of radiation in a way which he may *calculate* from observed readings of tube current, tube voltage, and target distance. Provided such measurements are accurately made, useful work can be done by using such a method. But, while such readings are desirable and give useful information, they are not sufficient. Sometimes filters are used, sometimes not; the filter may be changed; sometimes it is a surface area which is being treated, sometimes a region below the skin. How is an operator to know the change in intensity brought about by such changes in the conditions? Scattering of rays, moreover, profoundly affects the dose when treating deep-seated tissue. Again it is highly important that one radiologist be able to com-

pare his results with those of another working with a different tube and a different outfit. It is desirable, therefore, to have some simple *direct* means of measuring radiant energy.

125. This brings us to the all-important question of dosage and here again it is necessary that we clearly define exactly what we mean by an applied dose of x-rays. A beam of x-rays passes through the area or region to be treated and a certain amount of energy is absorbed. Certain biological changes take place and if the dose has been effective, a cure results. Now just what brings about the desired biological changes is not exactly known. Such changes may be directly proportional to the total amount of ionization in the tissue resulting from the absorption of x-rays, or they may be proportional to the absorbed energy which brings about the emission of corpuscles. Something is to be said for each of these assumptions, while both may be wrong. In any case, because of our lack of knowledge of exactly what is responsible for the biological changes, it is not possible to state what is the *absolute* dose. It *is* possible, however, to make use of certain properties of x-rays and so to establish practical and universal means of measuring the *physical* dose applied. By such means, an investigator may co-relate his work from day to day, as well as compare his results with other workers.

126. Since x-rays have different properties, several such physical means of measuring dosage may be and have been used. We shall first briefly note the most important of these.

(1) **Photographic**: In this method, as exemplified by the Kienböck strip, the dose is measured in terms of the amount of silver deposited from the emulsion on sensitized paper, or, in other words, by the degree of blackening resulting from the absorption of the rays.

(2) **Chemical**: In this method the dose is measured in

terms of the amount of iodine liberated from a solution of iodoform in chloroform.

(3) **Pastille**: Under this heading we place the methods Sabouraud and Noiré, Holznecht and Hampson, in all of which the dose is measured in terms of the change in color in certain salts resulting from the absorption of rays.

(4) **Electrical**: When light waves or x-rays fall on the substance selenium its electrical resistance alters. In the Fürstenau Intensimeter we have an instrument in which dosage is measured by making use of this property.

(5) **Ionization**: By the use of ionization chambers, or iontoquantimeters the dose may be measured in terms of the ionization produced in a medium such as air.

127. Now whatever the means adopted, there must be some standard, some unit in terms of which dosage may be applied. In medicine, so many grains, so many spoonsful are prescribed; what about x-rays? Obviously the unit adopted will vary with the property of x-rays utilized. In the photographic method, for example, it will have to bear some relation to the degree of blackening of the sensitive paper; in the chemical method, to the amount of iodine liberated. In all cases, however, the unit adopted, if at all satisfactory, should satisfy certain conditions: (1) It should be convenient, easily measured, reproducible, and should not vary from day to day. (2) It should be of such a nature that fractions or multiples of it may be used. (3) It should be applicable to the whole range of wave-lengths used in radiology. (4) Since in treatment we are concerned with the absorption of rays by tissue, and since the biological effect probably bears some direct relation to such absorption, the absorption of the substance used for measuring purposes should vary with the wave-length in a manner similar to the variation exhibited by tissue. Putting it in another way, condition (4) means that the ratio of the absorption by say 1 cm. of tissue to that of 1 cm. of the test substance should be the same

no matter what wave-length is used. (5) Finally, some idea of the "size" of the physical unit should be known in terms of its biological effect. Ten of the particular units adopted might either kill or cure. Moreover, the methods used by two men may be quite different and consequently their units of unequal "sizes." Ten of one man's units might be ineffective, while ten of another might be a bad overdose.

128. To consider the last point first, the difficulty is overcome by giving the size of all physical units in terms of what is called the Erythema Skin Dose or Unit Skin Dose (the E. S. D., or U. S. D.). When x-rays are absorbed by the skin in sufficient quantities, an erythema results. Here, then, is a definite simple biological effect to which all physical units may be related. It is necessary, of course, to define exactly what is meant by the E. S. D. Unfortunately, partly because of differences in human beings, partly because of its biological nature, this cannot be done as exactly as we define, say, a meter. According to Seitz and Wintz, the E. S. D. "gives rise, after five days, to a slight hyperemia which gradually subsides, leaving the skin undamaged though pigmented or tanned." (Morton.) In another reference,[1] the unit is defined as "that quantity of rays which causes a slight reddening of the skin after eight days and a slight bronzing of the skin after fourteen days." Probably there is little difference in these two.

Whatever the physical unit adopted, therefore, *by actual experiment,* its relation to the U. S. D. must be found. What this relation is will be given below when we examine some of the practical units which have been utilized in x-ray dosimetry. Before doing so, it is well to note that the physical dose will depend both on *the intensity* of the beam and *the time* of application (although it does not necessarily follow that a high intensity for a short time has the same effect as a feeble intensity for a long time). For

this reason physical means of estimating dosage may be divided into two classes: (1) those in which a direct measure of the *intensity* of the beam is combined with the time, (2) those in which the integrated effect of the beam for the whole time of application is obtained. The difference will be clearer from the specific examples which we shall now discuss.

The Kienböck Strip

E. S. D. = 10X.

129. In this method the degree of blackening produced in sensitive photographic paper by a dose of rays which gives rise to an erythema is arbitrarily called 10x. Lesser degrees of blackening correspond to subdivisions of the standard dose, and so units ½x, 1x, 2x, 3x, 4x, 5x, 7x, are also used. In actual practice the sensitive paper is placed on the skin of a patient, and a standard scale is supplied giving the shades corresponding to the standard and subdoses.

This method is therefore simple and convenient but does not lend itself to a high degree of accuracy. Moreover, it does not satisfy the fourth condition noted in section 127. That this is so, is evident from measurements made by Friedrich and Kroenig.[2]

130. In order to compare the absorption of various substances in use as dosimeters, with that of tissue, these investigators first of all showed that water is a good *phantom* for tissue. (By phantom we mean a substance which absorbs all kinds of rays to the same extent as tissue.) To compare water with tissue, the extent to which the intensity of different kinds of rays was reduced by a thickness of 5 cm. of water was compared with the reduction by 5 cm. of ground meat. The results are given in Table XIX, from which it will be seen that for all four kinds of rays (of increasing hardness) water absorbs, within one or two per cent, to the same extent as tissue.

TABLE XIX

Quality of Rays	*Absorption in 5 cm. water*	*Absorption in 5 cm. meat*
	Per Cent	Per Cent
Unfiltered	80.6	81.6
Filtered with 3 mm. Al.	68.4	70.0
Filtered with 10 mm. Al.	63.4	65.4
Filtered with 1 mm. Cu.	57.7	59.5

131. While discussing this question we may note in passing that it is a mistake to use aluminium as a phantom, 1 mm. being assumed to be the equivalent of 1 cm. of tissue. Although this has been done to some extent, the measurements given in Table XX clearly prove that while for soft rays, 1 mm. of aluminium absorbs much the same as

TABLE XX

Quality	*Absorption in Water*	*Absorption in Aluminium*
	Per Cent	Per Cent
Unfiltered rays, gap 20 cm.	82.7	75.1
" " gap 30 cm.	81.1	70.2
Filtered, 3 mm. Al.	71.8	53.4
Filtered, 10 mm. Al.	62.4	37.3
Filtered, 1 mm. Cu.	58.7	28.2

1 cm. of water, for more penetrating rays, it is much more transparent. Now as water is a good phantom for tissue for all kinds of rays, it is evident that aluminium is not, especially for very hard rays.

132. We return now to the Kienböck strip. In order to compare its absorption with tissue for a whole range of wave-lengths, Kroenig and Friedrich made a set of measurements on the relative absorption of water and of silver, the latter being one of the chief absorbing constituents of a photographic emulsion. Their results showed that "quite marked differences exist in the ratio of the amount of absorption in water and in silver with the different qualities of rays." To give an example, for unfiltered rays, the

ratio obtained was 0.93, for much harder rays (filtered through 1 mm. of copper) the ratio was 0.51. This then, is a decided objection to the use of the Kienböck strip for accurate work.

The Sabouraud and Noiré Pastille

E. S. D. = Tint B.

133. Until recently the pastille method has been used to a considerable extent by radiologists. As an example of its use we may deal with that of Sabouraud and Noiré. A salt of barium platino-cyanide in the form of a round pastille some 8 mm. in diameter is exposed to the rays, the pastille, in actual use, being placed on a metallic sheet at a distance from the target equal to one-half the distance from target to the patient. In this position the standard dose changes its color from the original pale green to a brownish yellow, called Tint B.

Other dosage "measurers" on the same principle which have been used are (1) Holzknecht's Quantimeter, E. S. D. = 5 H; (2) Bordier's Chromo-Radiometer, E. S. D. = Tint I; (3) Hampson's Radiometer, E. S. D. = 4 H.

In all of these, dosage is measured in terms of a change in shade, the standard dose in some cases being subdivided by the use of different tints. To assist in the observations "tintometers" may be used.

The use of pastilles, however, although convenient, cannot be recommended for exact work. By way of objection we cannot do better than quote Colwell and Russ.[3] "A simple experiment may show the misleading indications of these pastilles. A pastille is placed in the usual position and exposed to the rays from a very soft bulb, and the time noted to change its color to the standard tint; the bulb is then hardened and the current in the primary adjusted, so that a new pastille placed in position suffers

the same color change in the same time. The dose, as measured by these two pastilles, is the same yet the clinical effects upon the tissues are profoundly different in the two cases."

This is in line with the later quantitative work of Friedrich and Kroenig who showed that there are marked differences in the ratio of the absorption of water (and so of tissue) to that of platinum (the metal of the pastille salt), when the effective wave-length is altered. In other words, pastilles do not satisfy the fourth condition noted above.

134. The method of measuring dosage which is proving most satisfactory is based on the ionization produced in air when traversed by a beam of x-rays. In the next chapter this important method will be discussed in detail.

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1. Del Buono, *Amer. Jour. of Roent.*, X, 752, 1923.
2. "The Principles of Physics and Biology of Radiation Therapy," Kroenig and Friedrich, English Edition by Schmitz, Rebman Co., New York, 1922.
3. Radium, X-Rays and the Living Cell: Colwell and Russ; Bell and Sons.

CHAPTER XII

DOSAGE BY IONIZATION

135. By making use of the ionization in an air chamber we are provided with the only means which satisfies all the conditions given in Section 127. In this case the absorbing substance is air, whose absorption Friedrich and Kroenig have shown to change with the wave-length in the same manner as water (and therefore tissue). We shall therefore examine somewhat in detail the principles underlying the use of ionization chambers as dosage measurers.

In Sections 41, 42, the meaning of the ionization of a gas was explained, while in Section 76 attention was directed to the fact that a beam of x-rays ionizes a gas through which it passes. In the latter section it was also assumed that the intensity of a beam of x-rays was inversely proportional to the time of discharge of a gold leaf electroscope when the air surrounding the leaf was ionized by the rays. We wish now to know how this principle can be used for the accurate measure of dosage. It is applied in two different ways, (1) by the galvanometer method, in which case the *intensity* of the beam corresponds to a *steady* deflection of the instrument, (2) by an electrometer method, in which case one may *either* measure intensity by observing the time of discharge, in whole or in part, of a charged electrometer (for example, an electroscope), *or* one may measure the integrated effect of the rays over the whole time of application. To understand either of these methods, a few fundamental ideas must be clear.

Saturation Ionization Current

136. Suppose a circuit is made containing two insulated plates P and Q (Figure 103) a galvanometer G and a battery B. Generally speaking, if there is an air gap between P and Q, the circuit is not complete and no current is indicated by the galvanometer. (It will be recalled that a galvanometer is an instrument in which a *steady* deflection of the indicator corresponds to the magnitude of the current in the circuit. It is used for indicating feeble currents,

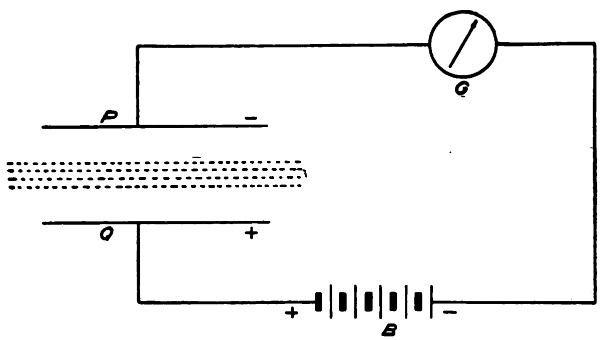


Fig. 103.—The galvanometer G indicates a current when x-rays pass between plates P and Q.

sometimes of an intensity equal to only one ten-millionth of an ampere.)

If, however, a beam of x-rays is allowed to traverse part of the space between P and Q, the air becomes ionized and the galvanometer now registers a current. From the work of sections 41 and 42, it should be clear that this current is due to a flow of positive ions to the negative plate P, of negative ions to the positive plate Q. Should the beam of rays be made more intense, more ions are formed, a bigger current results, and a greater deflection of the galvanometer. But once more the deflection will remain steady at the new value, provided conditions otherwise do not alter. With such an arrangement, therefore, *the more*

intense the beam, the greater the steady deflection of the galvanometer. We may, accordingly, take the galvanometer deflection as a measure of the intensity of the beam, *provided the ionization current has its saturation value.* (See Section 69.)

To obtain the saturation current, the potential difference (voltage) between P and Q must be great enough so that *all* the ions formed by the x-ray beam take part in the current. If the voltage is too small, some of the

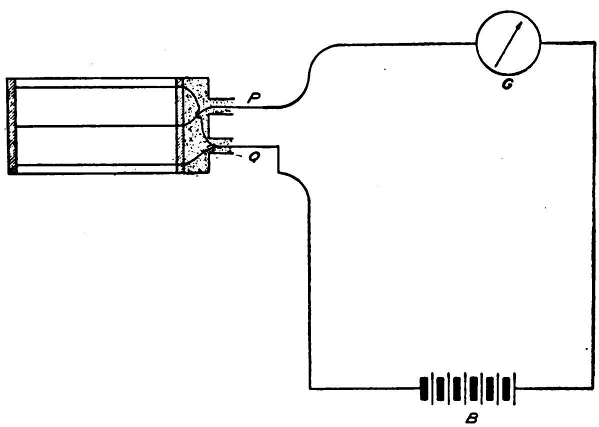


FIG. 104.—Arrangement for measurement of ionization current with galvanometer G and ionization chamber.

positive ions may unite with negative, or, to use the technical term, may re-combine before the ions reach the plates P and Q. The voltage, therefore, must be sufficiently high to prevent re-combination, or, in other words, so that as many ions reach the plate per second as are formed per second by the beam. When this is the case the current has its saturation value, and further increase in voltage can produce no increase in the current.

137. In the practical application of this means of measuring intensity, the plates P and Q with air space between correspond to what is called the *ionization chamber.* Regarding the most suitable form for such chambers, much

work has been done by Duane. In Figure 104 an illustration is given of a type in which saturation is obtained by a voltage as low as 20. In this form the central plate corresponds to P of Figure 103, while the two other plates (in electrical connection), correspond to Q. As the chamber is quite small and may be attached to the rest of the circuit by means of suitable long flexible leads, it can readily be moved about from place to place. The galvanometer, of course, is permanently set up on some suitable shelf where it is as free from external disturbances as possible.

With such an arrangement, therefore, the *intensity* of a beam at the ionization chamber is measured in terms of the steady deflection of the galvanometer. But, it is asked, what unit of dosage is used? Before answering that question it is necessary to recall one or two fundamental electrical ideas.

138. (1) What is called the absolute electrostatic unit of quantity is such that the force of repulsion between two such units placed 1 cm. apart in air is 1 dyne. (2) A current is measured by the quantity of electricity passing any point in a circuit each second. 1 ampere = 1 coulomb per sec. = 300,000,000 absolute electrostatic units per second. (3) The greater the volume of air ionized by x-rays, the greater the number of ions taking part in the ionization current. (4) It is, therefore, possible by measuring accurately the volume in which ions are formed to calculate from the observed galvanometer current the quantity of electricity contributed each second by each cubic centimeter of the ionized air, or, if you like, the ionized current due to each cubic centimeter.

Since this is the case, Dr. Duane has defined a unit of intensity which is of universal application. It is "That x-ray beam which would produce one absolute electrostatic unit of *current* in each cubic centimeter of air through which it passes, provided the current has its saturation value." It should be carefully noted that this unit, which

is denoted by the letter E, is a unit of intensity. The corresponding unit of dosage will therefore be one E unit applied for one second, and the dose applied will be expressed as so many E S units.

As an example of the magnitude of actual intensities when expressed in E units we give the following figures taken from a paper by Duane. With back-up 82,000 volts, tube current 5 ma., filter 2.6 mm. aluminium, the intensity at a tube distance of 40 cm. is 0.38 E. With back-up 200,000 volts, tube current 4 ma., filter ½ mm. copper, tube distance 80 cm., intensity = 0.21 E.

The Erythema Dose in E S Units

139. For the following information regarding the magnitude of the erythema dose, when expressed in E S units, the writer is indebted to Dr. Duane. With a beam of effective wave-length 0.15 to 0.16 A.U., of feeble intensity (about 0.07 E units), the erythema dose is 1500 E S units. This means, of course, that with a beam of such intensity the total time of application would be found from the simple relation $0.07 \times$ time in seconds $= 1500$, or the time $=$ $\frac{1500}{.07} = 21{,}428$ seconds = 5 hrs. 57 min. 8 sec.

Other workers give somewhat different estimates of the E.S.D. For example Dr. Duane reports, "The erythema dose used at the Massachusetts General Hospital is 800 E S, and that estimated by Dr. Pfahler of Philadelphia is about 700 E S. Some of the erythema doses estimated by men in the Middle West run in the neighborhood of 1400 E S." In this connection it is well to remember, as has already been pointed out, that because of its biological nature, there are bound to be differences in the estimates of different workers. There is a big difference in the re-action of different individuals, while the exact degree of erythema used as a standard by different investigators will not necessarily

be the same. But the important point which the writer wishes to emphasize lies in the fact that *to all workers 1 E S unit means exactly the same thing.* It is an absolute universal physical unit.

140. But, the radiologist objects, how is one with a very limited knowledge of physics to work out the intensity in these E S units? And even if one were able to do so, would not the time required in measuring volumes of ionized air, calibrating a galvanometer and so on render such a method far from simple? Now, as a matter of fact such a calculation would not even be possible with an ionization chamber such as illustrated in Figure 104, because of the effect of secondary rays from the walls of the chamber. Before it could be used for the calculation of the intensity of a beam in E units, comparison with a large standard air chamber (where effects of secondary rays are eliminated or taken into account) is necessary. What, then, is a radiologist to do? The answer is,—buy an outfit for which the necessary calculations have been made. There is no reason why a simple ionization set consisting of a chamber, galvanometer and scale (for reading deflection of the galvanometer) should not be sold *with the scale already calibrated* so that one could read directly in E units.

If such calibration were supplied and there is no reason why this should not be done, the above arrangement would be extremely simple and convenient for the practicing radiologist. With it he could:

(1) Read off directly from the scale the intensity of the beam utilized in any desired places; for example, following Duane, both where rays enter a patient and where they leave one.

(2) Measure the intensity at various depths by immersing the chamber in a water phantom. (See Section 130.)

(3) Measure the effective wave-length by the method already outlined in Section 112. (By means of such an intensity set, the particular thickness of aluminium which

reduces the intensity of a beam to the same extent as 1 mm. of copper could readily be found. Then the application of Figure 93 to find the effective wave-length is a simple matter.)

Finally, a radiologist so equipped would record his treatment in a manner which could give rise to no ambiguity anywhere, for he would give the quality in effective wave-length, the intensity in E units, and the time of application.

141. The method is not free from objections, one of which lies in the extreme sensitivity of the galvanometer required. Ionization currents are very feeble compared with currents ordinarily used, and to get readable deflections the instrument must be so sensitive that it is easily affected by vibrations and, moreover, easily broken. This difficulty may possibly be overcome by using some sort of amplifying arrangement such as one finds in radio sets. Indeed, in Europe a device has been put on the market which amplifies the ionization current to such an extent that an instrument not much more sensitive than a milliammeter may be used instead of the extremely sensitive galvanometer.

A more serious objection to the method lies in the fact that for most ionization chambers the calibration of the scale would not be the same for all wave-lengths. This may be lessened considerably by using chambers made of a substance of low atomic weight such as carbon, or, according to Kroenig and Friedrich, may be almost entirely eliminated, by the use of a chamber of cow's horn whose surface is made conducting by graphite. In any case the error would not be great provided the arrangement was utilized for only a small range of wave-lengths.

Intensity by the Use of an Electroscope

142. Suppose, instead of using the galvanometer, an electroscope is utilized, connections being made as shown in Figure 105. In this case, it will be seen, Q is joined to

earth (grounded), while the other plate P, which is insulated, is joined to an electroscope. Normally, when the insulated system of such an arrangement (that is, the plate P, connecting wire, and electroscope support) is given a charge of electricity, the leaf remains stationary. (See, however, Sections 41 and 42.) If, however, the air between the plates P and Q is ionized by a beam of x-rays, ions of a charge opposite to that on the electroscope system will be attracted to the plate P, and so the system will gradually have its charge annulled, and the leaf of the electroscope

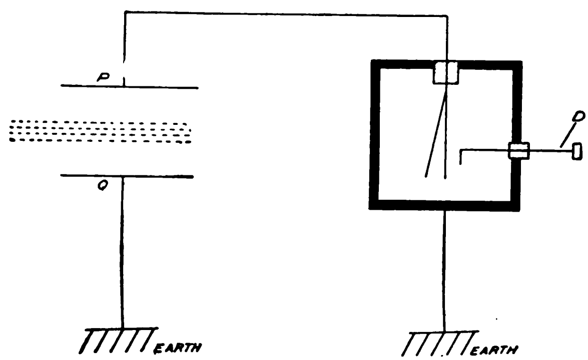


FIG. 105.—The electroscope is discharged when x-rays pass between plates P and Q.

will gradually fall. The greater the number of ions formed per second, the greater the number which go to the plate P, and hence the faster the leaf of the electroscope falls. In other words, *the intensity of the beam will be proportional to the rate at which the leaf falls.* Such an arrangement may, therefore, be used to measure intensity.

Here again, in actual practice, an ionization chamber corresponds to the plates P and Q, the arrangement used being somewhat similar to Figure 106. In this figure C represents a small ionization chamber, the insulated electrode E corresponding to plate P of Figure 105. This electrode is connected by the insulated wire K (which may be several meters long if desired) to the electroscope, care

being exercised to shield the conductor K from electric disturbances by surrounding it with the outer grounded metallic shield S. To prevent ionization in the region between K and the outer shield, the space may be filled with some insulating substance such as rubber. (This would be necessary unless the space between K and S were completely shielded from the action of x-rays.)

143. With this electroscope arrangement, then, intensity is measured by observing the rate at which the leaf falls, and not by reading a steady galvanometer deflection. In actual practice, therefore, the leaf is observed through a

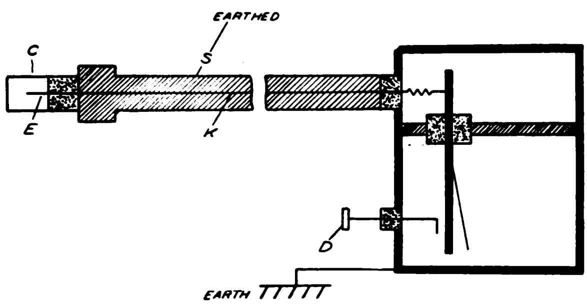


FIG. 106.—Arrangement for measurement of intensity of beam with ionization chamber and electroscope.

low power microscope (or in any other convenient way) and the movement over a scale is carefully timed. Intensities are directly proportional to the rate at which the leaf falls. In using the electroscope, however, care must be exercised to correct for "leakage." Even without the x-ray tube running, the leaf may fall slowly due to defective insulation, or to feeble ionization from other causes (radioactive substances about, for example. See again Section 42). With the tube in operation, leakage may result from ionization in parts of the apparatus other than the ionization chamber, for example, in the electroscope, if insufficiently protected, or in the tube connecting the chamber to the electroscope. Correction for such possible errors

should always be made. This can readily be done by taking readings of the fall of the leaf when the ionization chamber is carefully shielded from the beam of rays by means of thick lead. A simple example will illustrate the method.

Suppose we are comparing the intensities of a beam in two different places, and have observed the rate of fall of the leaf to be,—for the first place, 5 scale divisions per second; for the second, 2 divisions per second. Suppose also, when the ionization chamber was completely protected, the leakage fall was at the rate of 2 divisions per *minute*. Then, $\frac{\text{First intensity}}{\text{Second intensity}} = \frac{5 \times 60 - 2}{2 \times 60 - 2} = \frac{288}{118}$.
This follows because the ionization current due to the first intensity, when corrected for the leakage error, $= 5 \times 60$ or 300 divisions per minute less the leakage current of 2 divisions per minute. Similarly for the second intensity.

To use the electroscope to obtain E units, it is necessary to make use of a large standard ionization chamber (Section 140) and a calibrated electroscope of known capacity. But, here again, as in the case of the galvanometer method, there is no reason why a calibrated electroscope and corresponding ionization chamber should not be placed on the market. A description of such a calibrated set (although not in E units) is given in Section 146.

Electrometer and Direct Measure of Dosage

144. An electroscope (or electrometer of other type) may also be used to measure the integrated effect of the product (intensity $\times$ time of application). To utilize an electroscope for this purpose, the principle involved is identical with that employed in the arrangement of Figure 106. The only change lies in the increased capacity of the system which is discharged by the flow of ions in the chamber. The capacity may readily be increased by having in the vessel which houses the electroscope a condenser C (Figure

107) which by means of a movable contact L may be joined to the insulated rod of the electroscope. With the condenser thus joined, the capacity of the insulated system is much greater. This means that a much greater quantity of electricity must be given to the insulated system to deflect the leaf, say, one division, than is the case when the condenser is not attached. It follows, therefore, that the amount the leaf falls due to a transfer of a million, or any

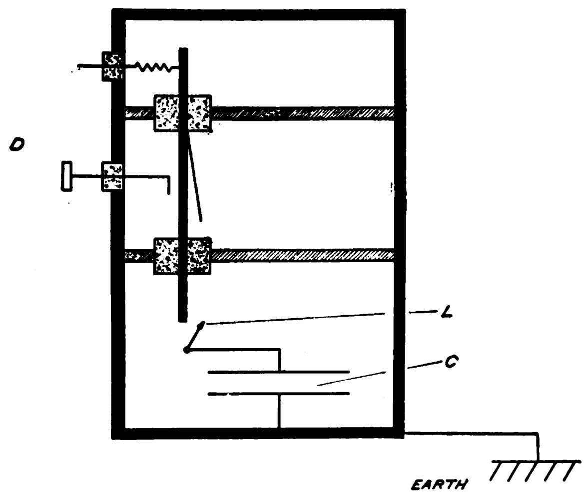


FIG. 107.—An electroscope whose capacity may be increased by addition of condenser C.

number, of ions in the chamber will be much less with such increased capacity than without. In other words, if a condenser of sufficient capacity is added, the fall of the leaf becomes very slow. By choosing a high enough capacity, the leaf may fall so slowly that at the end of the treatment the electroscope is still not completely discharged. In that case the fall of the leaf will be proportional to the *total* amount of ionization produced in the whole time of treatment, that is, to the product, intensity $\times$ time.

145. In this case, therefore, it is possible to adopt a universal unit of dosage, not of intensity. This has been

done by Friedrich and Kroenig, who measure the physical dose in terms of "the *quantity* of rays which transports in 1 c.c. of air by ionization, the quantity of electricity equal to an electrostatic unit, with a saturated current." This unit is represented by the letter e, and the erythema dose in terms of it is stated to be 165 e to 170 e.

This unit must not be confused with Duane's E unit which, once more, is a unit of intensity. The two, of course, are very closely related. An intensity of 0.5 E applied for 20 seconds, means that the total quantity of electricity transported in the ionization chamber (per c.c.) is 0.5×20 or 10 e. In other words 1 E S unit = 1 e unit, in which connection it should be pointed out that in view of the magnitudes of the erythema dose given above in section 139, it looks as if Friedrich and Kroenig's value should be multiplied by 10, that is, it should be 1650-1700 e or E S units.

Duane's method has the advantage that both the intensity and the time are given, for, as has already been pointed out, a feeble intensity for a long time has not necessarily the same biological effect as a big intensity for a corresponding short time. 100 e may mean 1 E for 100 seconds, 0.1E for 1000 seconds, and so on. Both units, however, are absolute and therefore adaptable for international usage.

Solomon's Ionometer

146. As neither of the above units has yet come into general use, nor has been sanctioned by any international agreement, we shall call attention to an ionometer now on the market, in connection with which a third ionization unit is made use of; one, moreover, which might also readily be universally adopted. We refer to Dr. Solomon's Ionometer, an instrument in which an ionization chamber and electroscope are used in a manner identical with that already described. The scale, however, is standardized

in terms of "the ionization produced by 1 gram of radium element in one second, placed at a distance (from the chamber) of 20 mm., and screened by 0.5 mm. of platinum." [1] This is called 1 R unit, the erythema dose being equal to 1000 R.

When, therefore, such an outfit is sold, the manufacturer supplies the number of R units which correspond to the full scale deflection of 50 divisions. As the electroscope may be used with and without a condenser, two constants are supplied, one for the small capacity, the other for the large capacity. To take a concrete case, in one such instrument, the fall of 50 divisions corresponds to 500 R units, or 10 R units per scale division (since there are 50 scale divisions) for the large capacity; to 130 R, for the small capacity. Suppose, then, in a certain treatment, with such an arrangement the total fall of the leaf (using large capacity) was 35 scale divisions. The dose applied is simply 10 R $\times$ 35 or 350 R, that is, about one-third of an erythema dose.

By using the small capacity, the same apparatus may be used to measure intensity. For example, suppose a beam causes the leaf to fall 50 divisions in 65 seconds (using small capacity now). Since the supplied constant in this case is 130 R, this tells us that in 130 secs. the leaf fell through 50 divisions, with the radium in the proper position. In other words, since an intensity of 1 R per second causes a fall of 50 divisions in 130 secs. the intensity which causes the same fall in 65 secs. must be $\frac{130}{65}$ or 2 R per sec.

It will be seen then that this ionometer uses an electroscope to measure either intensity or dosage by applying exactly the same principles as those already described. The difference is solely in the unit adopted. But here again it is an absolute unit, because it is based on the ionization produced by a definite amount of radium under specified conditions. This unit, however, is also not in general use,

and the world still awaits a general agreement for an international unit of x-ray radiation. It is in the interests of both physicists and radiologists that an international unit should be adopted as speedily as possible.

147. Before leaving the subject of ionization, we wish briefly to refer to a method of measuring dosage in which a portable ionization outfit [2] is used without the necessity of having a *calibrated* electroscope. In this method, the intensity of the beam of rays must be measured (in the usual way, by observing the rate at which the electroscope leaf falls) for a series of increasing thicknesses of a standard filter material, copper or aluminium. By making a graph of the results, one obtains, (1) the thickness of the filter which produces homogeneity. The test is that already discussed in section 84, namely,—equal thicknesses of the filter reduce the intensity of a homogeneous beam by the same amount. (2) The percentage of the radiation transmitted by such a thickness of filter. (3) The value of D, the half absorption thickness, which describes the quality of the rays. (If the graph is plotted on semi-logarithmic paper, this amounts to the same thing as reading off the change in the logarithm of the intensity per millimeter of filter thickness.)

From this information obtained by the operator, combined with universal data supplied with the ionization outfit, it is possible to find very simply (a) the effective wave-length, which obviously depends on the value of D, (b) corresponding to each percentage obtained in (2) above, a number giving the product "milliamperes × minutes" which is necessary to produce an erythema. This number then becomes the unit corresponding to the E. S. D. and treatment is applied in terms of fractions or multiples of it.

References:

1. Gough, *Phys. Soc. London,* 35, 41D, June, 1923.
2. *Jour. of Radiology,* IV, 335, 1923.

CHAPTER XIII

DEEP THERAPY

148. Most, if not all, readers are familiar with the fact that x-rays are used for treating diseased conditions both on the surface of the body and at various depths below it. In the last chapter we have tried to show how the radiologist can measure radiation in such a way that it is possible for him always to use definite and comparable doses in such treatment. While such methods are applicable to the treatment of both superficial and deep-seated tissue, in the latter case certain additional factors must be taken into consideration. The following paragraphs are devoted to a brief discussion of the most important of these.

In treating deep-seated tissue, since the diseased area may be several inches below the skin, it is obvious that the effective wave-length of the beam utilized must be very short; in other words, that the tube must be operated on very high voltage. In Section 139, for example, we have noted that Duane uses an effective wave-length of .15-.16 A.U. This means (applying the relation given in Section 107), that the voltage must be greater than $\frac{12354}{.15}$ or 82,000 volts. As a matter of fact, since the shortest wave-length is less than the effective, the voltage required is probably considerably greater than 82,000. In actual practice, potentials ranging from 100,000 to 250,000 are used.

149. Now the use of very high voltages means that additional precautions must be taken to make sure that there is adequate protection both against electrical shock, because of defective insulation, and against possible injury from the

more penetrating rays used. An operator must ever be on the watch to see that both he himself and the patient

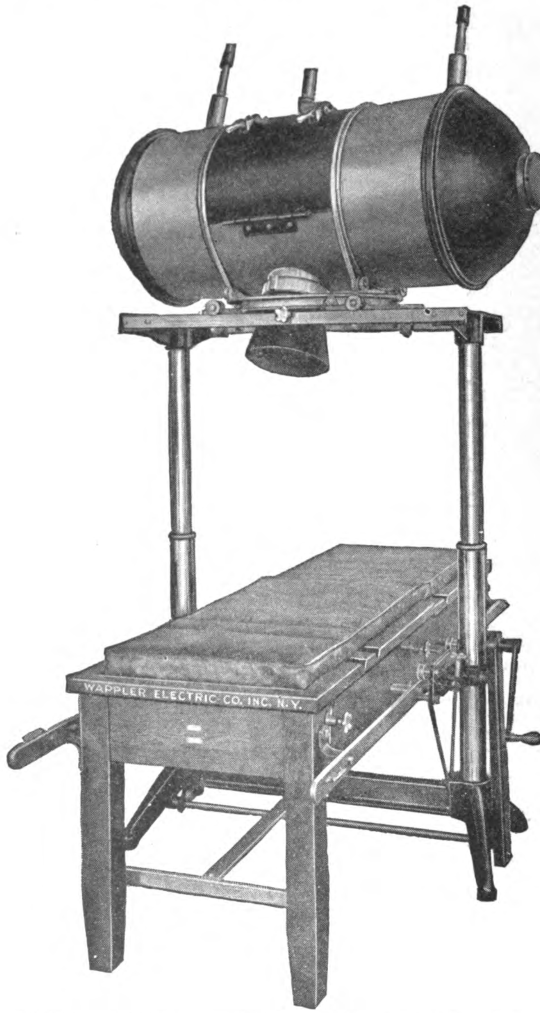


FIG. 107A.—Tube Holder for use in Deep Therapy (Wappler Electric Co.).

are properly protected. As far as the patient is concerned, probably the best means of protection consists in having the whole x-ray apparatus, tube and all, in a separate room.

Duane, for example, suspends a bulb below a hole in the ceiling of a room, while the patient receives treatment comfortably lying on a mattress on the floor of the room above.

In most cases the tube is enclosed in a holder which is supposed to provide protection against both electrical

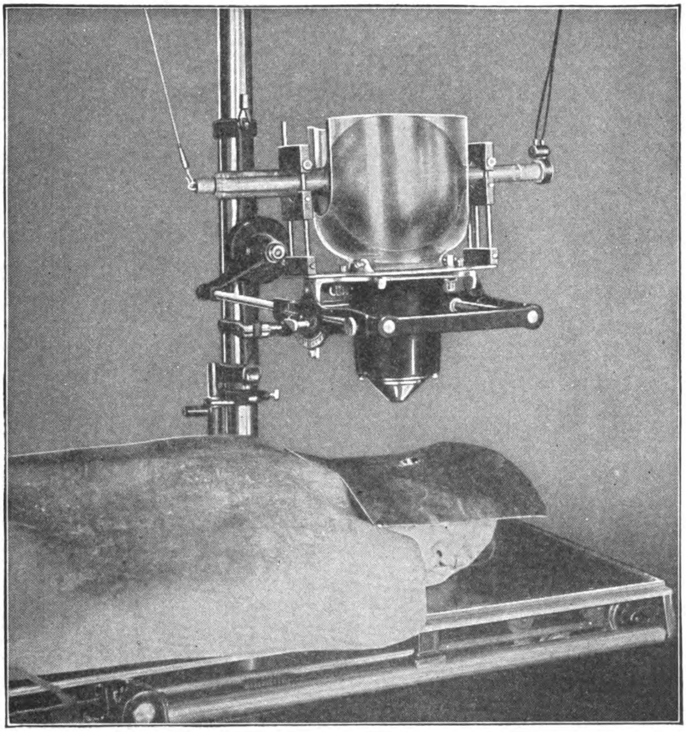


FIG. 107B.—Showing protection of patient in local treatment (Victor Electric Corporation).

shock and against stray radiations (Note Figure 107A). Purchasers of such protective holders should make sure that they are made in accordance with the protection rules already noted (Section 91). In any event it is a safe precaution to cover the body of the patient (except, of course, at the port of entry) with an ample thickness of some protective material. (See Figure 107B.)

A third danger is found in the noxious fumes and bad air generated when very high potentials are used. It must be remembered that in deep therapy it is not a matter of taking exposures for a few seconds but of giving treatment, possibly for several hours. This point, therefore, is very important. To improve conditions in this respect, at least one firm has on the market a tube holder from which the fumes and bad air may be removed by means of an auxiliary suction pump, while the foul air is replaced by a supply of freshly filtered air. Details of various tube holders will be found in advertising literature and in the references given below.[1]

150. It is obvious that to deliver x-radiation to any deep-seated tissue, the beam of rays must pass through the skin and intervening tissue. A certain percentage of the radiant energy, therefore, will be absorbed by this normal healthy tissue. Moreover, if the beam is at all heterogeneous (as is almost always the case to some extent), practically all of the softer, longer wave-length will be completely absorbed by the intervening tissue. Now because of this absorption there is always the danger that this tissue may be seriously injured. A first principle in deep therapy, then, is that treatment must be so regulated that no serious injury is done to superficial tissue. This is done by paying attention to several factors.

(1) The soft components of a beam must be removed by high filtration. This has the added advantage that the beam utilized will be fairly homogeneous, a condition which according to Dessauer is essential for proper deep therapy. So necessary is the presence of a filter that safety devices are frequently used to make sure that it has not been omitted. Pfahler, for example, has an electrical arrangement, by means of which a bell rings continuously if the filter is not in place. Copper, zinc and brass are all suitable materials to use for filters (Section 111).

Because the hard primary beam may cause an emission

of characteristic rays from the filter itself, it is sometimes necessary to remove such a radiation by adding (on the side of the filter next the patient), a layer of some absorbing material. Substances of low density, such as wood or leather, may be used for this purpose. (See Section 117.)

(2) By using as high voltage as possible and consequently the most penetrating as well as the most homogene-

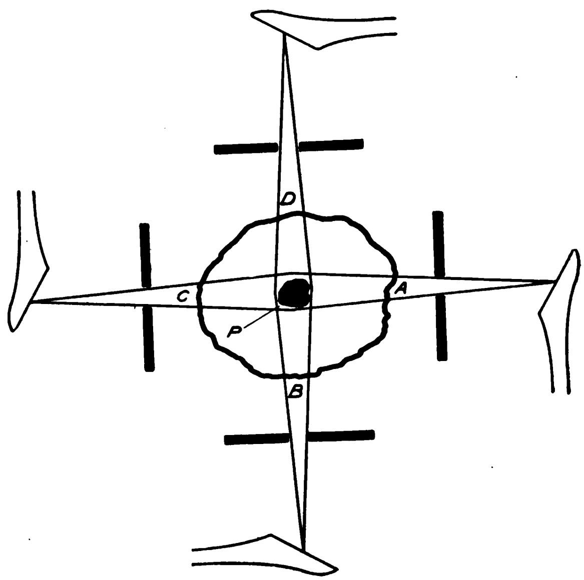


FIG. 108.—Method of cross-fire treatment.

ous rays, the percentage of the surface intensity which exists at any given depth, is increased. This follows at once from the fact that the more penetrating the rays, the less the absorption by the intervening tissue.

(3) By using the method of "cross-fire" treatment, the absorption by the superficial tissue in any one place is considerably lessened. The principle of this method, which is very simple, will be clear from a glance at Figure 108, where P represents a diseased area within the body which is treated through four ports of entry, A, B, C and D. If

the correct dose is delivered to P in four instalments, one through each of the ports, it is evident that the superficial tissue in each case absorbs only one-quarter of the radiant energy which it would have absorbed had only one port been used. In passing it may be noted that for the proper use of this method, actual measurements of the dimensions involved must be made or estimated as closely as possible and a certain amount of elementary geometry applied. But once again, for each port of entry, the maximum dose which may be delivered is limited by the tolerance of the normal intervening tissue. Any effect exceeding an erythema must not be produced.

(4) Judgment must be used in the choice of the most suitable distance of target to patient. It must be remembered that, no matter what the distance is, the intensity at the surface is always greater than at any depth beneath it. This means that the absorption per unit volume in the superficial tissue is always greater than that per unit volume of the region treated. It follows, therefore, that the greater the fraction of the surface intensity which is delivered to a diseased area, the easier it will be to give the proper dose without superficial injuries. To make the matter concrete, suppose a region 10 cm. below the skin is to be treated with one of two beams, for the first of which the intensity at this depth is 45 per cent of the surface intensity; for the second, only 35 per cent. Obviously the 45 per cent beam would be preferable, because in that case the energy absorbed at the surface would be $\frac{100}{45}$ or 2.2 times that absorbed by the treated area, whereas in the case of the the other beam the ratio would be $\frac{100}{35}$ or nearly 3.

Now what has all this to do with the target-skin distance? Simply this, that for a given depth of tissue the ratio of the depth intensity to the superficial value depends on this distance. Suppose a tumor is situated b cm. (Figure

109) below the surface; it is not difficult to prove that if the distance target-to-skin is increased (say from a_2 to a_1), the intensity of the rays at the tumor becomes a greater fraction of the superficial intensity. For example (if we neglect absorption for the time being), when the target-skin

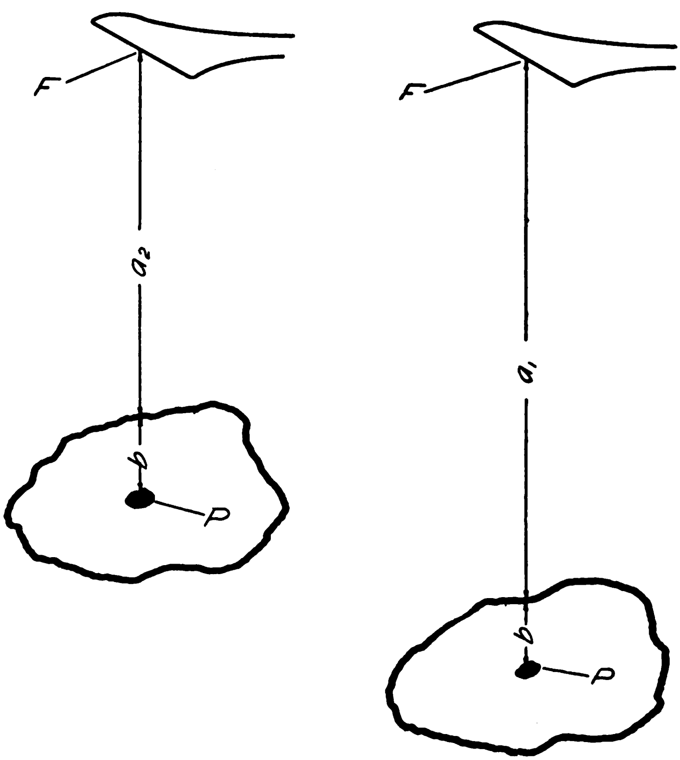


FIG. 109.—Target at two distances for same tumor depth.

distance is 19 times the tumor depth the intensity at the tumor is 90 per cent of that at the surface; if the target distance is made 8.5 times the tumor depth, the intensity cannot be greater than 80 per cent; while if the target distance is only 25 cm., for a tumor depth of 10 cm., the intensity at tumor cannot be greater than 50 per cent of the surface value.

These numbers simply deal with the decrease in intensity which takes place because of the law of the inverse square, or if you like, because of the divergence of the beam. In addition, there is, of course, always the decrease in intensity due to the absorption of the b cm. of tissue. *This, however, is always the same for any target-skin distance,* so that we may conclude that, the greater the distance of the target, the greater the percentage of the intensity at the tumor. On the other hand, the farther removed the target, the longer the exposure. Practically, therefore, the most suitable distance must be chosen with due consideration to each factor. In actual use, the writer has found recorded distances 62 cm., 50 cm., as low as 23 cm., and as high as 100 cm.

(5) In the case of a lesion near the surface, it is sometimes stated that the percentage received by the area treated may be increased by covering the skin with a layer of some substance which absorbs much the same as tissue. (Paraffin wax, beeswax, dough, are examples of substances which have been used.) This, however, is not true unless the rays used are only moderately hard, with a fair admixture of soft rays. Some actual numbers will make the point clear.

Suppose a semi-superficial tumor 1 cm. below the skin is to be treated with hard rays for which the tissue absorption is accurately given by the numbers in Tables XXI (an actual set due to Friedrich and Kroenig).

TABLE XXI

Depth	0	1	2	3	4	5	6	7	8	9	10
Intensity	100	89	87	77	69	60	51	47	42	37	31

According to these numbers the intensity of the beam at the tumor is 89 per cent that of the skin, or in any treatment, the skin receives $\frac{100}{89}$ times the radiation received

by the tumor. Now suppose we cover the skin with a layer of say, paraffin wax, 8 cm. thick. In that case, the tumor is 9 cm. below the paraffin surface, the skin 8 cm. Since the paraffin absorbs much the same as tissue, it follows from the numbers of Table XXI that if the intensity at the paraffin surface is 100, at the skin it will be 42 per cent, at the tumor 37 per cent. In other words the intensity at the tumor is now $\frac{37}{42} \times 100$ or 88 per cent of that at the skin, a shade less than without this covering layer of paraffin. With such rays, therefore, there is no such advantage.

On the other hand, if one uses unfiltered rays of moderate penetration, such for example as are given in Table XXII, there is some gain in this respect.

TABLE XXII

Depth	0	1	2	3	4	5	6	7	8	9	10
Intensity	100	81	65	53	43	35	29	24	19.4	15.9	13.1

Applying these numbers to the same supposed case, we find that with the covering layer of paraffin, the intensity at the tumor would be $\frac{15.9}{19.4}$, or 82 per cent of the skin intensity—a slight gain, but scarcely enough to justify the use of such a method unless there are other advantages. (With softer rays, the advantage would be more marked.) According to Morton, "central lesions are probably the easiest to treat with accuracy." In that case one advantage of using such a covering layer is found in the undoubted effect it has of changing a semi-superficial lesion into a central one.

DOSAGE IN DEEP THERAPY

151. We pass now to a consideration of the actual dose delivered to the diseased area. How is it possible to meas-

ure the amount of radiant energy absorbed by a region within the human body? While in a few cases it is possible to insert a small ionization chamber right into a cavity (as has been done by Friedrich and Kroenig), from the nature of the problem, in most cases such direct measurements are out of the question. By the use of a phantom such as water, however, indirect measurements may be made. If, then, a radiologist wishes to know how much the intensity of a beam is reduced in passing through 8 cm. of tissue, he can do one of two things.

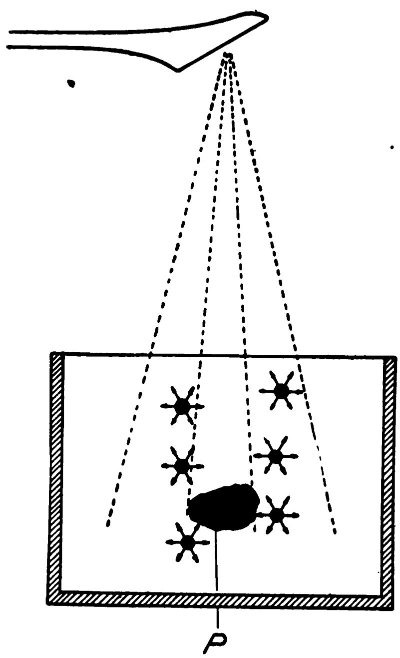


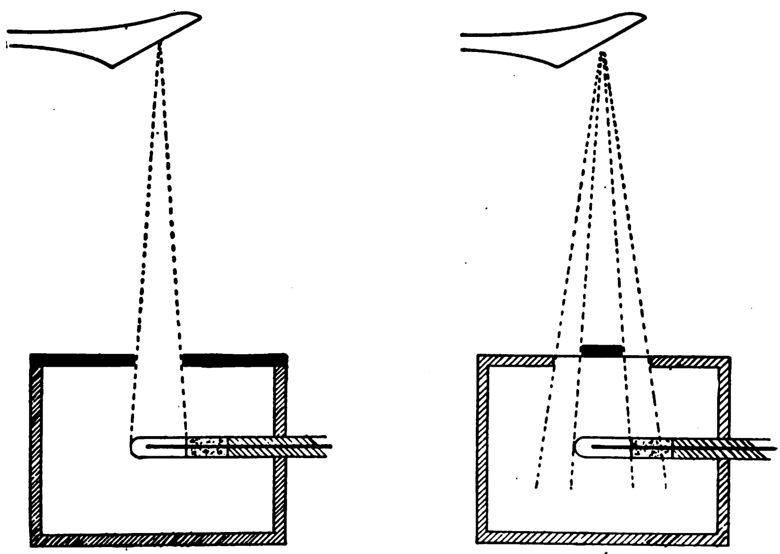
FIG. 110.—The body P is radiated by both primary and secondary rays.

(1) By using some means of comparing intensities (preferably ionization), he can find by actual experiment the change in intensity which takes place when the ionization chamber, for example, is removed from a position on the surface of water to a point 8 cm. below. The percentage change found will correspond fairly closely to the change produced by 8 cm. of tissue, since as already noted several times, the absorption of all kinds of rays by water is the same as by tissue.

(2) He can make use of standard charts, such as have been made by Dessauer, showing the variation in the intensity with increasing depth. For the intelligent use of either method, certain fundamental facts of great impor-

tance in deep therapy must be taken into consideration. These will now be briefly discussed.

152. Secondary radiation plays a part in deep therapy even more important than that of the primary beam. From what has been stated in Chapter X, it should be evident then an object P (Figure 110), placed within any scattering medium receives radiation both from the primary beam



a *b*

FIG. 111.—(a) Ionization chamber receives both primary and secondary radiation; (b) chamber is protected from primary beam.

from the target and from secondary rays originating from particles in the scattering medium which surrounds the object. That this is the case has been well shown by Friedrich and Kroenig. Two sets of readings were taken, (1) with an ionization chamber placed as in Figure 111a, so that by means of the lead diaphragm it receives radiation from the primary beam directly; (2) placed as in Figure 111b, so that the chamber was screened from the primary beam, but might receive secondary radiation from the dispersing medium through which the primary beam passed.

Their readings showed that the intensity due to secondary radiation could be as much as four times greater than that of the primary. In other words, the dose contributed by secondary rays in deep therapy may be as high as 80 per cent of the whole.

Now some years ago tables were published in which the intensity at various depths of tissue were given as a result of *calculation* based on the half absorption value of tissue and the law of the inverse square, but without any consideration of the effect of scattered radiation. Such tables, therefore, are absolutely useless. To illustrate the point some measurements of Friedrich and Kroenig are again quoted. With a certain set-up (that is, with rays of a certain effective wave-length), the intensity 10 cm. below the skin, as calculated from a consideration of the above two factors, was 10 per cent of the surface intensity. By actual measurement with the ionization chamber the intensity at the same depth was 44 per cent of the skin value! Such tables, therefore, can only be obtained with any degree of accuracy by making actual measurements, if possible, with living tissue; failing that, in some suitable phantom such as water. Tables of this sort have been carefully made, notably by Dessauer, who has published charts from which the intensity at various depths may readily be obtained. In using these charts it must be remembered that the numbers will vary with the quality of the rays used, with the target distance, and with the size of the port of entry (see Section 153). A typical set due to Glasser [2] is given in Table XXIII, where the numbers give the percentage intensity at the center of a field, with port of entry 20 cm. $\times$ 20 cm.; 200,000 volts (crest) across tube; filter, 0.75 mm. copper + 1 mm. aluminium; target-skin distance 30 cm.; effective wave-length = 0.15 A. U.

In connection with the use of even a good phantom such as water, it should not be forgotten that at the best no phantom can correspond exactly to highly complex tissue.

TABLE XXIII

Distance	0	2.0	3.2	4.6	6.0	7.8	10.0	12.8	17.0 cm.
Intensity ...	100	90	80	70	60	50	40	30	20

While tissue in the main is composed of substances of low atomic weight, in the human body we have also to do with such elements as calcium and iron. It is possible, therefore, that characteristic rays from such substances may have an important therapeutic effect. "The therapeutic effect of x-rays often manifests itself pronouncedly in the proximity of bones. This is probably due in part to characteristic radiations emitted by the calcium and other constituents of the bones." (Kaye.) Moreover, the intensity may be considerably altered by the presence of air cavities near the place treated. In spite of such difficulties the use of phantoms permits of a standardized technique as a result of which exact data may be accumulated. Correct physical doses can be obtained even if all the factors taking part in the biological action are not known.

PORT OF ENTRY AND DEPTH DOSAGE

153. In the use of such tables, it is highly important that all conditions conform to those for which the numbers have been given. With the effect of varying voltage, wavelength, filtration, and target distance, the reader should be fairly familiar; we have yet to show the effect of a change in the area of the port of entry. As secondary radiation is responsible for such a large fraction of the total depth dose, it should not be surprising to learn that the magnitude of the dose at any depth depends on the size of the cone of rays used. The reason is simple enough. A glance at Figure 110 will show at once that the larger the volume radiated around the region P, the greater the number of particles there are to contribute secondary rays. This is

borne out by actual measurement. Kroenig and Friedrich, for example, have shown that with a port of entry 12 cm. × 12 cm., the dose at a depth of 8 cm. in water is almost twice that obtained, at the same depth, with a port 4 cm. × 4 cm. The effect, of course, does not increase indefinitely with increase in port area, little increase being found beyond an area 20 cm. × 20 cm. (focal distance 30 cm.). The reason is obvious — there is a limit to the thickness of water which can be penetrated by the secondary rays.

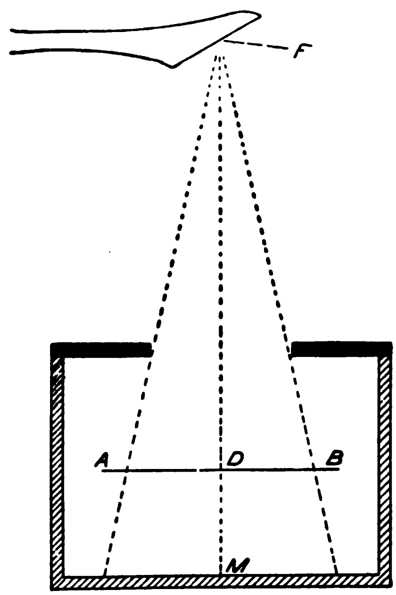


FIG. 112.—Intensity of radiation is not the same at all points along ADB.

Both the numbers of Table XXIII, and the data of the last section, refer to the intensity of the radiation at points in the *center* of the field of radiation, that is, in Figure 112, along the line FDM. It is not to be expected that the intensity at all points at the same depth, along the line ADB, for example, should be the same. At B (a point on the edge of the field of radiation), secondary rays will be received only from particles to the left, whereas at D secondary radiations are contributed by particles on all sides. The intensity at B, therefore, will in general be less than at D. For this reason the charts of Dessauer and Glasser, to which reference has already been made, consist of a series of curved lines, called "isodose" curves, formed by joining all points across the field for which the intensity of radiation is the same.

154. In making phantom measurements to find out the percentage depth dose careful attention must be paid to another factor. This has to do with the position of the ionization chamber when readings are taken at the surface. The point may best be illustrated by referring to some measurements of Weatherwax and Leddy.[3] Using an ionization chamber only about 1 cm. in width (similar in size and style to that of Friedrich and Kroenig) these radiologists compared the intensities of a beam when the chamber was placed in several different positions near the surface. Their results are given in Table XXIV.

TABLE XXIV

Position	*Intensity*
In air	66.4
On surface	95.7
Half submerged	98 5
Fully submerged	100.0
5 mm. below surface	97.7

NECESSITY OF STANDARDIZATION

155. These results show the importance of specifying exactly the conditions under which measurements are made. There is a variation of over 4 per cent between positions when the chamber is just touching the water (95.7) and just submerged (100).

Obviously the remedy for this and many other possible causes of error lies in the adoption of a standard technique. Sooner or later international standards will be adopted in radiology as they have been done in all branches of science where measurements are necessary. In this respect good progress has already been made, as the writer has tried to show in dealing with the use of ionization chambers for the measurement of dosage. In the meantime, in every case of treatment published, it is important that conditions of operation should be given exactly—the quality of rays;

tube current; tube voltage (accurately measured); filter; depth dose; target-skin distance; size of port; and so on. By this means coöperation between different workers is possible, and ultimate standardization is bound to come. Already much data has been accumulated—so much so that the particular percentage of an erythema dose which is correct for the treatment of different diseases is sometimes definitely stated. With such questions, however, it has not been the aim of the writer of this book to deal; rather has he sought to explain something of the fundamental physical principles without a knowledge of which no sound advances in radiology are possible.

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3. Weatherwax and Leddy, *Amer. Jour. of Roent.*, X, 488, 1923.

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